Arnold Schwarzenegger
Governor

MAP-BASED REPOWERING OF THE ALTAMONT PASS WIND RESOURCE AREA BASED ON BURROWING OWL BURROWS, RAPTOR FLIGHTS, AND COLLISIONS WITH WIND TURBINES

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Map-Based Repowering of the Altamont Pass Wind Resource Area Based on Burrowing Owl Burrows, Raptor Flights, and Collisions With Wind Turbines is a final report (Contract Number 500-01-032). The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

The Altamont Pass is both a significant wind resource area and important raptor-use area. Raptor flight patterns and burrowing owl burrow locations have been associated with fatalities caused by wind turbines, indicating wind turbine siting can influence collision rates. This study sought to develop maps of areas within the Altamont Pass where wind turbine operations might be safer for burrowing owls principally, and other raptors secondarily, and which could be used to guide the relocation of existing wind turbines to safer locations and to guide the siting of wind turbines installed in repowering projects. The positions of sampled raptor flights and burrows of burrowing owl, ground squirrel, and pocket gopher were related to a 10-meter digital elevation model of the study area. Two models were developed that successfully predicted burrowing owl suitable locations when validated by on the ground surveys. On average, burrowing owl burrows were lower on the slope than ground squirrel burrows, and they were on smaller and shallower slopes. Maps of likely burrowing owl burrow locations were produced, and wind turbines operating on the predicted locations of burrowing owl burrows also associated with greater mortality of burrowing owls and some other raptor species. Moving wind turbines away from these likely burrowing owl burrow locations should help reduce burrowing owl mortality in the Altamont Pass Wind Resource Area.

Keywords: Altamont Pass Wind Resource Area, burrowing owl, burrows, fuzzy logic, GIS, raptors, ground squirrels, mortality, pocket gophers, wind turbines

Executive Summary

Introduction

The locations of most of the wind turbines existing in the Altamont Pass Wind Resource Area (APWRA) were established in the absence of information pertaining to patterns of bird flights, perching, or nest locations, and such information may have led to minimizing impacts to birds. Most wind turbines were also mounted on short towers that inadvertently positioned the blades of the turbine rotors at the height domains of most flights of golden eagle, red-tailed hawk, American kestrel, and other species often killed by wind turbines in the APWRA. An opportunity exists for carefully repowering the APWRA by replacing the old-generation wind turbines with modern turbines on taller towers and positioned where research has shown collision risk to be least.

Purpose

This study mapped areas within the APWRA where wind turbine operations might be safer for birds and that could be used to guide the relocation of existing, dangerously located wind turbines to safer areas and to guide the siting of wind turbines installed in repowering projects.

Project Objectives

The study's first objective was to develop predictive models of burrowing owl burrow locations within the Altamont Pass because the density of burrowing owl burrows near wind turbines had already been positively correlated with fatality rates. The second objective was to characterize raptor flights observed during visual scans, with an emphasis on how the flights related to topography and wind conditions at the times of the observations. The third objective was to test whether observed fatality rates of burrowing owls and other raptors related to the map-based predictions of burrowing owl burrow locations to determine whether a hazards map could help guide wind turbine sitting in careful repowering.

Approach

Raptor flights were observed and their positions mapped during 2002 and 2003 in areas where fatality searches at wind turbines had been performed from 1998 until 2003. During the same study, burrows of burrowing owl, California ground squirrel (Spermophilus beecheyi), and pocket gopher (Thomomys bottae) were mapped using Global Positioning System within multiple areas of the APWRA, which together included 571 wind turbines. The positions of burrows and sampled raptor flights were related to a 10-meter digital elevation model of the APWRA. The digital elevation model (DEM) was composed of 2,281,169 grid cells, of which 187,908 covered the burrow mapping areas and within which spatial relationships were tested and models developed. The grid cells were categorized according to their slope characteristics by a series of data processing steps using a geographic information system. These steps brought objectivity to deciding where boundaries should divide hilltop features from valley bottoms, as otherwise the transitions in slope are gradual and no clear boundary exists. Additional grid cell attributes included slope gradient, slope size, and the cell's position on the slope relative to the valley bottom or ridge crest. Two modeling approaches were used to develop mapped likelihood surfaces on which burrowing owl burrows were predicted to occur, based on slope variables developed from the digital elevation model. However, the raptor flight data were related to the digital elevation model visually and using univariate statistics, due to small sample sizes per species.

Project Results

Both modeling approaches produced maps of likelihood surfaces that comprised a minority of the study area but included disproportionately more burrowing owl burrows, indicating they could be used to predict future burrowing owl locations in the APWRA. Burrowing owls selected to reside in ground squirrel burrows that were lower on slopes than most squirrel burrows, and most squirrel burrows were already lower on slopes than the average DEM grid cell. Burrowing owl burrows were also located on smaller and shallower slopes than was the average ground squirrel burrow, and ground squirrel burrows were on smaller and shallower slopes than was the average DEM grid cell. These distinct patterns appeared to be independent of elevation and likely reflected the species' needs to evade predators.

The rate of burrowing owl fatalities caused by wind turbines within the likelihood surfaces predicted to contain most burrowing owl burrows was nearly double the rate observed off the likelihood surfaces. Where the models predicted burrowing owl burrows to occur, wind turbine-caused fatality rates were also higher for red-tailed hawk, mallard, western meadowlark, and mourning dove. Within the areas of the APWRA that were outside the areas predicted to include burrowing owl burrows, and that were leeward to the prevailing northwest and southwest wind directions, measured fatality rates at wind turbines were lower for burrowing owls, golden eagles, barn owls, western meadowlarks, and mourning doves.

Fatality rate estimates revealed inter-specific differences in the likely effectiveness of wind turbine siting guided by the predictive models presented herein. Wind turbine locations safer for burrowing owls appear more hazardous to great horned owls, as an example. One map-based solution may not reduce wind turbine-caused fatality rates of all bird species.

Conclusions and Recommendations

Assuming wind turbine siting can explain most of the variation in bird collisions, then moving wind turbines from within to outside the areas predicted to include burrowing owl burrows might reduce average annual fatalities of burrowing owl 74 percent, golden eagle 26 percent, American kestrel 49 percent, and all raptors as a group by 33 percent. However, it might not change red-tailed hawk or great horned owl fatality rates. Moving wind turbines outside areas predicted to support burrowing owls and to the leeward aspects of slopes relative to prevailing wind directions might reduce fatalities by about 30 percent for golden eagle , 39 percent for burrowing owl , 88 percent for barn owl , and 23 percent for all birds. However, doing so might increase fatality rates of red-tailed hawk mortality about 45 percent, American kestrel 16 percent, and great horned owl nearly 300 percent. Fortunately, compared to existing, old-generation wind turbines, a larger percentage of the planned and recently installed new-generation wind turbines occur outside the areas predicted to include burrowing owl burrows.

This percentage could be adjusted up, however, to minimize fatalities of several rarely occurring raptor species.

Caveats

Confounding factors potentially affecting the fatality associations could include:

- More end-of-row wind turbines occurring in the areas predicted to include burrowing owl burrows because these areas are low on the slope where turbine rows often end.
- Lower density turbine fields in the areas predicted to include burrowing owl burrows.
- Burrowing owl fatalities attributed to wind turbine collisions when they were really killed by predators.

Past research indicated end-of-row turbines and turbines in low density turbine fields associate with disproportionately more raptor fatalities. A confounding factor potentially affecting the predictions of burrowing owl burrow locations could be burrowing owl avoidance of wind turbines. All these factors could be better understood through additional research, which could also help verify the predictive models developed in this study.

Benefits to California

This study developed a modeling approach for predicting levels of direct impacts to birds caused by wind turbines in the Altamont Pass Wind Resource Area. The approach can be applied to all species for which suitable data exist and to any wind farm location in California. It can significantly improve the effectiveness of siting wind turbines for minimizing or reducing avian fatalities and can therefore lessen the adverse environmental effects of wind power development and of California's Renewables Portfolio Standard.

1.0 Introduction

The Altamont Pass (AP) is both a significant wind resource area (WRA) and important raptor use area. Thousands of operating turbines have caused a disconcerting number of bird deaths annually (Orloff and Flannery 1992, 1996; Smallwood and Thelander 2008; Alameda County Avian Monitoring Team 2008). The locations of most of the wind turbines existing in the APWRA were established in the absence of information pertaining to patterns of bird flights, perching, or nest locations, and such information may have led to minimizing impacts to birds. Most wind turbines were also mounted on short towers that inadvertently positioned the blades of the turbine rotors at the height domains of most flights of golden eagle, red-tailed hawk, American kestrel and other species often killed by wind turbines in the APWRA. To reduce the APWRA's impacts on birds, Smallwood and Thelander (2004) concluded that aside from permanently shutting down all the turbines to avoid bird fatalities, careful repowering would be more effective than any of the 16 mitigation measures they examined. Careful repowering would be replacement of existing wind turbines with modern turbines on taller towers and positioned where research has shown collision risk to be least. They also recommended measures to reduce fatalities in the absence of repowering, and Smallwood and Spiegel (2005a,b,c) elaborated on these measures, assigned wind turbines to categories according to collision threat (referred to as *tiers* for priority shutdown), and concluded that the most effective mitigation measure would be to shut down the wind turbines over the winter months.

To facilitate careful repowering, Smallwood and Neher (2004) analyzed raptor flight patterns from data supporting the Smallwood and Thelander (2004) study to further investigate flight patterns of raptors. Smallwood and Neher (2004) attempted to understand how raptors fly within the APWRA by relating flight locations to landscape attributes and wind conditions.

The study's objective was to forecast avian fatality rates in the repowered APWRA under two scenarios first conceptualized by Richard Podolsky (Personal communication, January 14, 2005). The first scenario was to be the repowered APWRA according to the 1998 Environmental Impact Report (EIR) and subsequent planning documentation, and was referred to as the *Power Maximizing (P-max) Scenario*. The second scenario was to be the same number and types of wind turbines as proposed in the 1998 repowering EIR and subsequent planning documentation, but arranged within the APWRA's boundary according to the results from careful examination of the bird behavior data intended to minimize avian fatality rates, referred to as the *Bird Fatality Minimizing Scenario (F-min)*. The authors hypothesized that the *F-min* scenario would aggregate wind turbines into higher-density turbine field areas, exclude wind turbines from ridge saddles, valleys, and the prevailing windward aspects of ridges and hills because these are some of the most dangerous locations based on raptor flight patterns.

F-min would likely result in less power generation than *P-max* because some of the sites that would be excluded to minimize fatalities would also be favored wind sites for power generation. Nevertheless, the goal was for *F-min* to yield a much smaller ratio of bird deaths to megawatt-hours of power generation, and the authors hypothesized *P-max* would yield a smaller ratio of fatalities to power generation compared to the ratio currently experienced in the APWRA. This hypothesized smaller ratio of fatalities to power generation due to repowering is supported by the results of WEST, Inc., (2006) and Smallwood (2006), who reported that the small Diablo Winds repowering project reduced bird fatality rates about 70% after its first year of operations.

Smallwood and Neher (2004) produced preliminary results of this study and outlined the proposed next steps for this study. However, this study deviated slightly from the earlier outline. Rather than building map-based repowering scenarios solely on raptor flight data, the authors also used burrowing owl burrow locations. The authors took this approach because there was a lack of data on burrowing owl flights and because the burrowing owl is one of the principal species killed by wind turbines in the APWRA (Smallwood and Thelander 2008; Smallwood et al. 2007). Since Smallwood et al. (2001) reported that burrowing owl collisions associated with the number of burrowing owl burrows within 55 meters of wind turbines, it was reasonable to assume that predicted burrowing owl burrow locations would correspond with known collisions.

2.0 Study Area

The APWRA encompassed about 16,450 hectare in eastern Alameda and southeastern Contra Costa counties in Central California. The study area ranged 78 to 470 m above mean sea level, composed of hills, ridges and valleys, with stock ponds, small seasonal ponds, and marshes. Most ridges, were oriented northwest to southeast, bisected by seasonal streams. Hills and ridges increased in size toward the west.

Vegetation was predominantly non-native annual grassland, including soft chess (Bromus *hordeaceus*), rip-gut brome (*Bromus diandrus*), foxtail barley (*Hordeum murinum leporinum*), Italian rye grass (*Lolium multiflorum*), and wild oats (*Avena fatua*). Common forbs included black mustard (*Brassica nigra*), fiddle-neck (*Amsinckia menziesii intermedia*), chick lupine (*Lupinus microcarpus* var. *densiflorus*), bush lupine (*Lupinus albifrons*), and wally baskets (*Triteleia laxa*). Grasses and forbs grew during the rainy months (January – March), then died or went dormant by early June. In addition to the dominant annual grasslands, other vegetation communities and physiographic elements included alkali meadow, emergent marsh, riparian woodland and scrub, creeks and drainages, stock ponds, cultivated land, and rock outcrops. Landowners in the APWRA principally grazed livestock but also leased land to wind companies.

The APWRA included about 5,400 wind turbines of various models at the beginning of the 1998 study by Smallwood and Thelander (Figure 1), with a total rated capacity of about 580 megawatts (MW). The variation in models corresponded with variation in revolutions per minute and MW. Toward the end of their study in 2003, about 5,301 wind turbines composed the APWRA, but some of these were non-operational. The wind turbines were mounted on various types of tower at heights ranging 4 to 43 m above ground. Many were on ridge crests or on ridgelines that descend into ravines from the ridge crests. About 11% of the wind turbines were within large drainage basins we referred to as canyons, which could include gullies and ridges, and some ridge crests occur at lower elevations than the canyon boundary. Other wind turbines occurred on hill slopes away from ridges and drainages.

In 2005, the Diablo Winds Project replaced 105 150-kW and 25 250-kila watts Flowind vertical axis wind turbines with 38 Vestas 660-kW turbines (Photo 2). By the end of 2006, the Buena Vista Wind Energy project replaced 170 Windmaster, Nordtank, and Danwin turbines with 38 1-MW Mitsubishi turbines (Photo 3). Repowering is also planned for the Tres Vaqueros portion of the APWRA, where Howden 330-kW wind turbines currently operate.

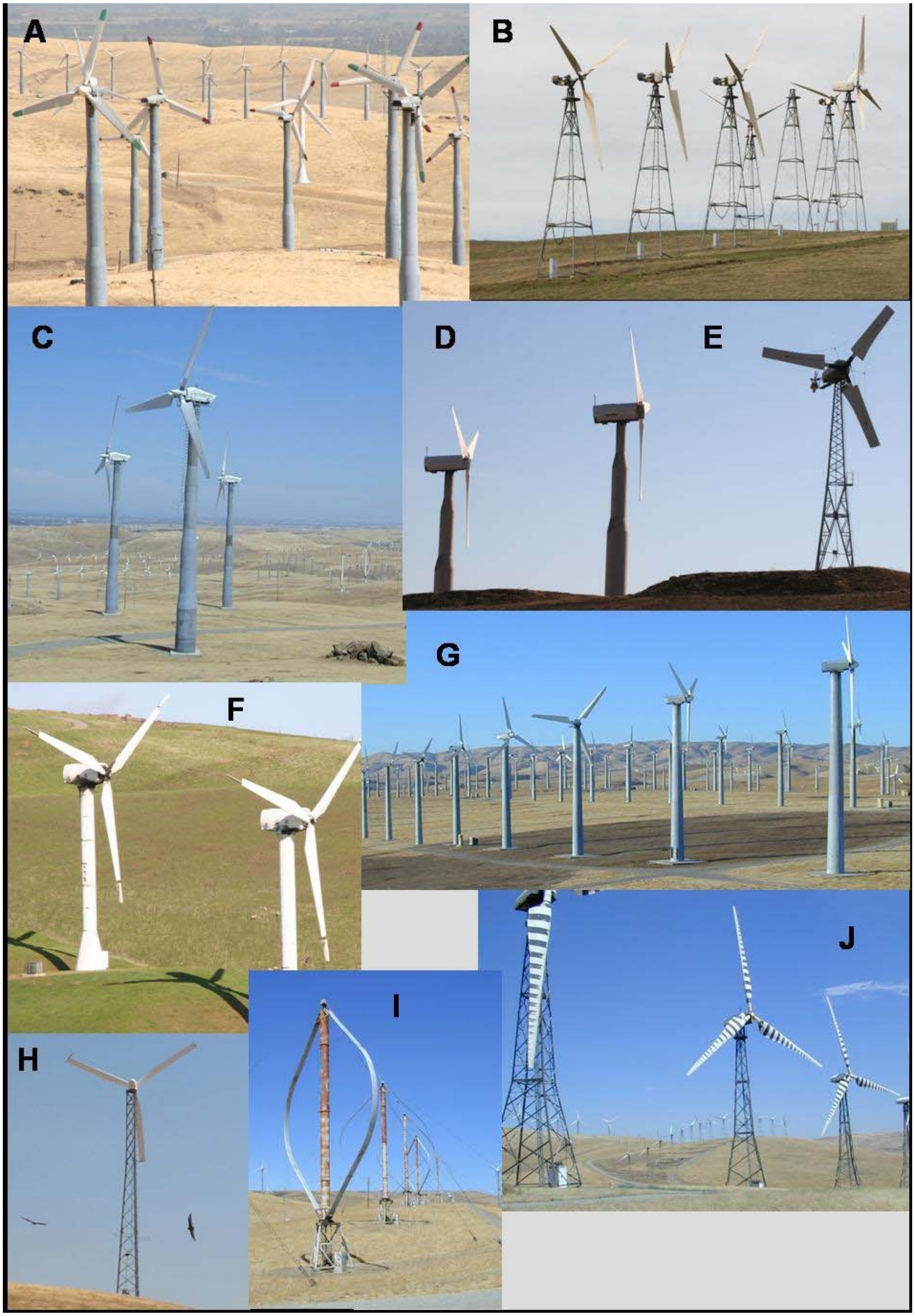


Figure 1. Some of the various old-generation wind turbine models in the APWRA during the Smallwood and Thelander (2004) study, including Nordtank 65-kW (A), KCS56 100-kW (B), Bonus 150-kW (C), Polenko 100-kW (D), Windmatic 65-kW (E), Howden 330-kW (F), Micon 65-kW (G), Enertech 40-kW (H), Flowind 150-kW (I), and KVS-33 400-kW (J). These photos are not to scale.

Photo Credit: K Shawn Smallwood

Figure 2. Vestas 660-kW turbines in Diablo Winds Energy Project, which replaced Flowind vertical axis turbines seen in Panel I of Photo 1.

Photo Credit: K Shawn Smallwood

Figure 3. Mitsubishi 1-MW turbines in Buena Vista Wind Energy project that will replace Windmaster, Nordtank, and Danwin turbines.

Photo Credit: K Shawn Smallwood

3.0 Methods

3.1. Fatality Searches

Smallwood and Thelander (2008) described fatality search methods, and the following summarizes those methods. From March 1998 through September 2002, biologists searched for bird carcasses within 50 m of 1,526 wind turbines arranged in 182 rows, referred to as Set 1. Groups of wind turbines were periodically added to the search rotations as access was granted, and about 67% of the remaining turbines were sampled between November 2002 and May 2003, amounting to another 2,548 turbines arranged in 380 rows, referred to as Set 2. The selection of wind turbines was not random due to access restrictions, but the large number of wind turbines sampled extended across the study area and encompassed the range of conditions present across the study area. Search intervals for avian fatalities varied inter-annually and among groups of wind turbines, averaging 53 ± 11.6 days among wind turbines in Set 1 and >90 days for turbines in Set 2.

Two biologists explored the ground around each wind turbine row, walking transects about 6 m apart. All carcasses or body parts found were examined to assign it species, age, sex, and probable cause of death. Cause of death was determined by evidence of injuries, when available, such as burn marks or singed feathers typical of electrocution, and cut or twisted torsos, dismemberment, and other forms of blunt force trauma typical of collisions with wind turbine blades. Otherwise wind turbine collision was the assumed cause of death for carcasses found near turbines. The number of days since death was estimated after assessing carcass condition (e.g., fresh, weathered, dry, bleached bones) and decomposition level (e.g., flesh color, presence of maggots, odor). Time since death was used to estimate which season the fatality occurred and to decide whether to use the fatality in fatality rate estimation.

Avian fatality rates due to wind turbines was expressed as the number of fatalities per MW per year, where MW was the rated power output of the wind turbines composing a row of wind turbines, and the number of years or fractions of a year were the time spans over which searches were performed at that wind turbine row. Fatality rate was estimated only for fatalities caused by wind turbines ≤90 days before each search, and 0.25 years was added to the number of years used in each fatality rate calculation to represent the period when fresh carcasses could have accumulated prior to the first search. Normally, fatality rate estimates are adjusted for carcasses not found due to searcher detection error and scavenger removal (Smallwood 2007), but adjustments were unnecessary here because the fatality rate estimates were compared only within the wind farm and were not being extrapolated or compared to other locations. However, the authors assumed scavenger removal rates did not vary across the APWRA, which may not hold true.

3.2. Raptor Flight Observations

Smallwood and Thelander (2004) described the methods used to observe raptor flights in the APWRA. The following is a summary of those methods. Two biologists collected bird behavior data within 60 observation plots (referred to as OPs) from October 15, 2002 through May 14, 2003.

Boundaries of study plots encompassed wind turbines that were easily visible to observers from a fixed observation point, resulting in a mosaic of contiguous plots. Although the 60 plots were not randomly selected, they covered the entire area studied during the behavior research performed during 1998 through 2000 (Smallwood and Thelander 2005), as well as the wind turbines searched for fatalities over the longest period. Figure 4 depicts the observed raptor flight locations where Smallwood and Thelander (2004) performed the behavior observation sessions. Boundaries are not shown in Figure 4 but correspond generally to the clusters of red circles representing raptor locations.

These plots encompassed 1,500 wind turbines, with 6 to 52 wind turbines per plot. Each observer carried maps of the plots to identify each turbine by its number designation and to link it to bird observations. Maps included stitched ortho-photos so the viewer could see the distribution of wind turbines and the underlying physical relief, roads, and other features observable in the field. A 300 m-buffer around the target wind turbines was added to the map to help observers plot field observations and in deciding when birds arrived or left the sampling area.

At each plot, two observers performed 360° visual scans using 8×40 binoculars to 300 m from the wind turbines within the plot. After each 30-minute observation session, the observers moved to the next sampling plot to begin another 30-minute session. Each plot was sampled four times, no more than once every three to four weeks. Behaviors were observed in various weather conditions, except when rain or fog reduced observer visibility to <60% because these conditions prevented observers from accurately observing bird activity.

During each 30-minute session, observations of raptor were recorded at the end of each minute during the session. Each raptor that appeared within 300 m of a wind turbine in the plot was assigned a letter according to its sequence of raptors entering the plot. The authors also assigned a number to each raptor to represent the minute into the session when the observation was made. The observation of the first raptor entering a plot after the first minute of the session was reported as A1, and the observation of a second raptor entering the plot after the first minute was reported as B1. The next observations of these two birds at the end of the next minute were reported as A2 and B2. A bird that left the 300-m buffer around the wind turbines but remained within sight of the observer retained its original identification letter. Birds that disappeared from sight for >30 seconds were considered different individuals and assigned the next available letter designation if and when the bird reappeared. While this likely led to double counting individual birds in some instances, it prevented misclassifying two individual birds entering the plot at different times as one bird. Data were recorded on maps and digital voice recorders, which allowed attribute data to be later linked to the mapped locations of entries. Audio recordings were transcribed to a spreadsheet within 48 hours.

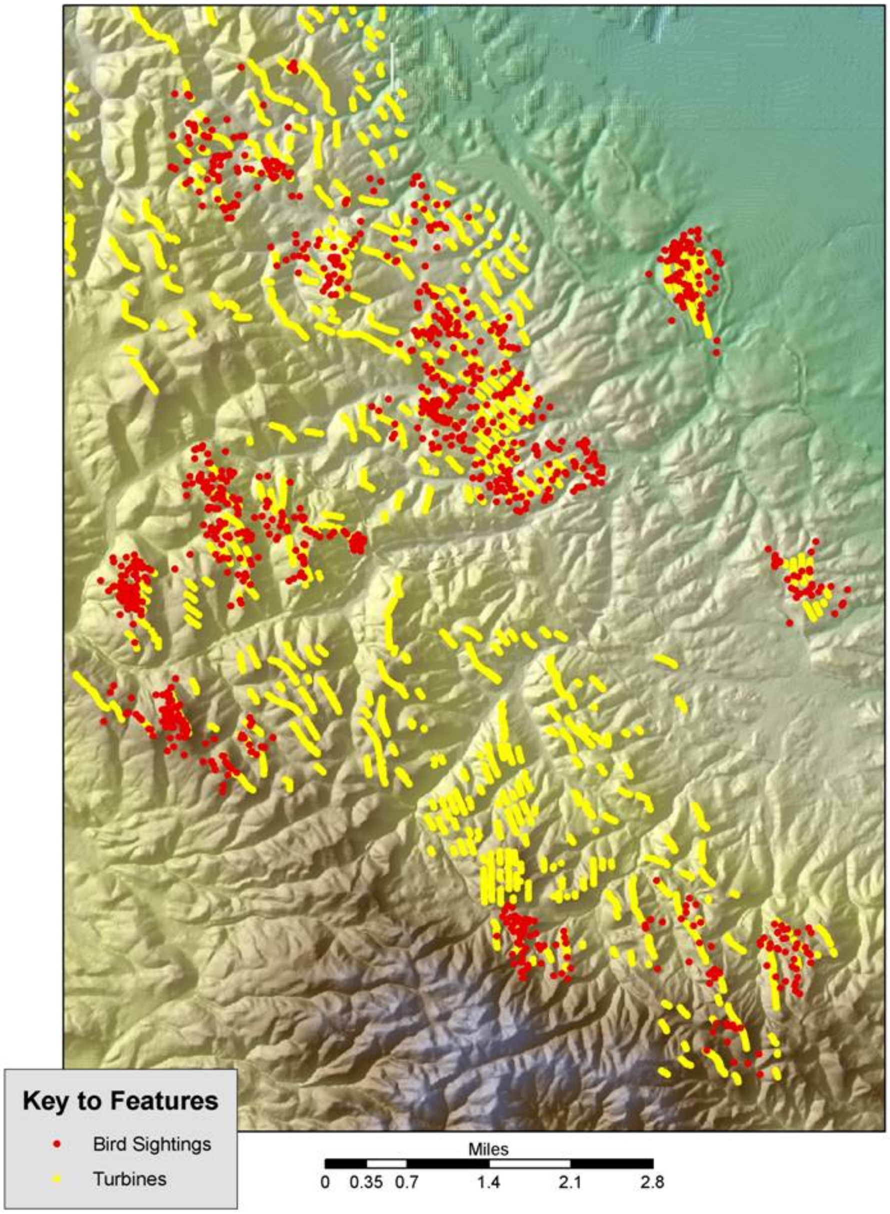


Figure 4. Observed raptor flight locations (red circles) during behavior sessions where they performed during 2002 and 2003. Yellow symbols denote wind turbines. Generally, areas lacking red symbols were not included in the raptor observation sessions.
Source: Lee Neher

In addition to data collected each minute, particular behavior events were also recorded whenever they occurred during the session. For example, observations were recorded of birds flying through the row of wind turbines, as were observations of birds landing or interacting with other individuals. Observers also recorded individuals to species, perch used, flight behavior (Table 1), height above ground, and positions of each observation.

At the start of each 30-minute session, the observers recorded measurements of temperature, wind speed, and wind direction, and noted weather conditions (e.g., cloud cover, rainfall, fog level) and which specific wind turbines were operating. For analytical purposes, wind force was later measured on the Beaufort scale, where 0 was <0.3 m/s, 1 was 0.3 to 1.5 m/s, 2 was 1.6 to 3.3 m/s, 3 was 3.4 to 5.4 m/s, 4 was 5.5 to 7.9 m/s, 5 was 8 to 10.7 m/s, 6 was 10.8 to 13.8 m/s, and 7 was > 13.8 m/s. The observers left the premises for safety reasons when winds reached >15 m/s, which were near gale winds.

Table 1. Flight behaviors recorded during 30-min observation sessions in the study plots.

Flight Behavior	
1. Fly through	11. Soaring column
2. Gliding	12. Surfing
3. Soaring	13. Ground hopping
4. High soaring	14. Fly-catching
5. Contouring	15. Fleeing
6. Circling	16. Interacting
7. Kiting/hovering	17. Flocking
8. Diving	18. Flushed
9. Mobbing/chase	19. Land
10. Mobbed	20. Mating

Source: K. Shawn Smallwood and Lee K. Neher

The locations of bird observations were digitized using ArcMap GIS 9.2 and geo-referenced aerial imagery available at Lawrence-Livermore National Lab (LLNL). All of the attributes of each bird observation were then geo-referenced to the coverages of the APWRA landscape created by LLNL. The subsequent geo-processing steps are described below under the section titled **Burrowing Owl Spatial Distribution**.

3.3. Mapping Burrowing Owl and Mammal Burrows

Smallwood mapped burrows of mammals and burrowing owls using a Trimble Pro-XR GPS within 90 m of 571 wind turbines composing 70 rows. Selected turbine rows represented a wide range of raptor fatality rates recorded during fatality searches, as well as a variety of physiographic conditions and levels of effort to control rodent populations in the APWRA. Levels of rodent control were none, intermittent, and intense, where intense control effectively eliminated ground squirrels from the treated areas. Ground squirrel and pocket gopher burrow systems (i.e., complexes) were mapped using a pacing method to separate burrow systems when continuity of sign rendered inter-burrow system distinctions difficult (Smallwood and Erickson 1995). Burrow systems of pocket gopher typically contain one adult pocket gopher, whereas burrow systems of ground squirrel can contain multiple adults. In the case of pocket gophers, the pacing method can lead to an estimate of the adult population, but it can be used as index of abundance for ground squirrels. Transects were searched 0, 15, 30, 45, 60, 75, and 90 m away from the turbine row, thus covering increasingly larger areas around the turbine rows.

Areas intervening standard burrow mapping areas were also mapped in some turbine fields, including:

- 66 ha with 131 Micon 65-kW turbines arranged in 7 rows near Mountain House.
- 57 ha with 120 Vestas 100-kW turbines in 8 rows just south of Old Altamont Road in the central portion of the APWRA.
- 21 ha with 29 Enertech turbines arranged in 5 rows near the Seawest office.
- 14 ha with 18 Micon 65-kW wind turbines in 5 rows off Midway Road.
- 15 ha with 15 Flowind 150-kW and Bonus 150-kW turbines in 4 rows on the Elworthy Ranch.
- 26 ha with 24 Bonus 120- and 150-kW turbines in 4 rows on the Elworthy Ranch.
- 32 ha with 30 Bonus 120-kW turbines in 5 rows on the Elworthy Ranch.

Intervening areas were mapped between other rows of wind turbines, as well, but these were relatively small areas.

Burrowing owl burrows were identified after burrowing owls flushed from the burrow or by sign. Sign included pellets, whitewash, shed feathers, and/or nest displays composed of cattle dung, toad skins, lizard carcasses, other animal parts, and/or arranged sticks. Not all burrows mapped were nest burrows, but only 1 of ≥2 burrows was mapped when burrows occurred ≤25 m apart, which was closer than the closest inter-nest distance reported by Green and Anthony (1989).

3.4. Burrowing Owl Spatial Distribution

Mapped burrowing owl burrows were characterized as point features in ArcMap GIS and layered onto a digital elevation model (DEM) of the areas searched for burrows. The location of each burrowing owl burrow was characterized by slope aspect, slope grade, rate of change in slope, direction of change in slope, and elevation (see Smallwood and Thelander [2004] and Smallwood and Neher [*2004*] for details on how these variables were used). These variables were also used to generate raster layers of the study area, one raster[1] expressing the aspect of the corresponding slope (hereafter referred to as (*slope aspect*), and the other expressing whether the landscape feature was tending toward convex versus concave orientation. These features were defined using geoprocessing at LLNL.

[1] A *raster* is a grid and is composed of equal-sized grid cells.

The existing United States Geological Survey (USGS) 10-m DEM was used as a starting point for characterizing the terrain of the Altamont Pass. To replace poorer quality data across about 25% of the study area, geo-referenced USGS 7.5′ digital raster graphics (DRG) were used with GIS to capture the contour lines (hypsography). These contour vectors were then run through ESRI's Topograph tool to create a 10-m DEM, which was inserted into the existing USGS 10-m DEM. Elevation was assigned to each grid cell according to its centroid.

From the final DEM of the Altamont Pass region, the statistical analyses were limited (masked) to data within the areas searched for burrows used by fossorial mammals and burrowing owls. The resulting analytical grid was composed of 187,908 10x10-m cells. The analytical grid was used to develop and test predictive models, which were later projected across the 2,281,169 grid cells composing the APWRA. The analytical grid was not selected randomly from within the APWRA because the focus of the burrow mapping was on raptor prey species nearby the wind turbines, most of which were placed along ridge crests and ridgelines between peaks and valley bottoms. Thus, some landscape features within the analytical grid were disproportional to their occurrence within the APWRA, such as ridge crests. Model predictions will be more reliable for landscape features represented within the analytical grid than for landscape features typically farther away from wind turbines.

The authors used the Curvature function in the Spatial Analysis extension of ArcGIS 9.2 to calculate the curvature of a surface at each cell centroid. A positive curvature indicated the surface was upwardly convex at that cell, a negative curvature indicated the surface was upwardly concave, and a value of zero indicated the cell surface was flat. The curvature data (-51 to 38) were classified using the NaturalBreaks (Jenks) function with classes of curvature – convex, concave and mid-range. The break values were visually adjusted to minimize the size of the mid-range class. The authors used a series of geoprocessing steps called "expand," "shrink," and "regiongroup," as well as "majority filter tools" to enhance the primary slope curvature trend of a location. The result was a surface almost exclusively defined as either convex or concave (Figure 5). The convex surface areas consisted primarily of ridge crests and peaks, hereafter referred to as ridges, and the concave surface areas consisted primarily of valleys, ravines, ridge saddles, and basins, hereafter referred to as *valleys*.

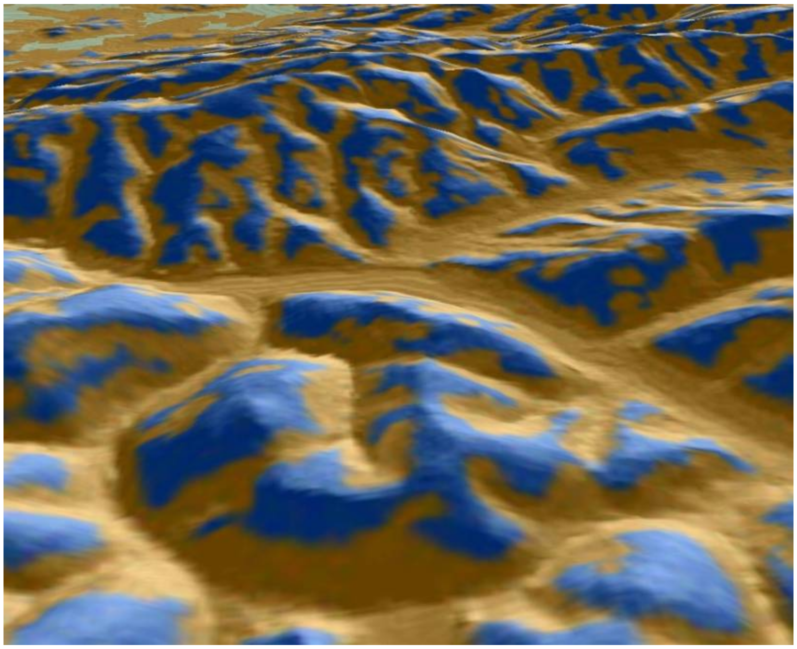


Figure 5. Ridge and valley features expressed as blue and gold, respectively, and typical of convex-trending groups of DEM grid cells (ridges) and concave-trending groups of grid cells (valleys).
Source: Lee Neher

Line features representing the estimated average centers of ridge crests and valley bottoms (Figure 6) were derived from the following steps. ESRI's Flowdirection function was used to create a flow direction from each cell to its steepest downslope neighbor, and then the Flowaccumulation function was used to create a grid of accumulated flow through each cell by accumulating the weight of all cells flowing into each downslope cell. A valley started where 50 upslope cells had contributed to it in the Flowaccumulation function, and a ridge started where 55 cells contributed to it. The flowdirection and flowaccumulation functions were applied to the ridges by multiplying the DEM by -1 to reverse the flow. Line features that represented ridges and valley bottoms were derived from ESRI's gridline and thin functions, which feed a line through the centers of the cells composing the valley or ridge. Thinning put the line through the centers of groups of cells ≥40 in the case of valleys.

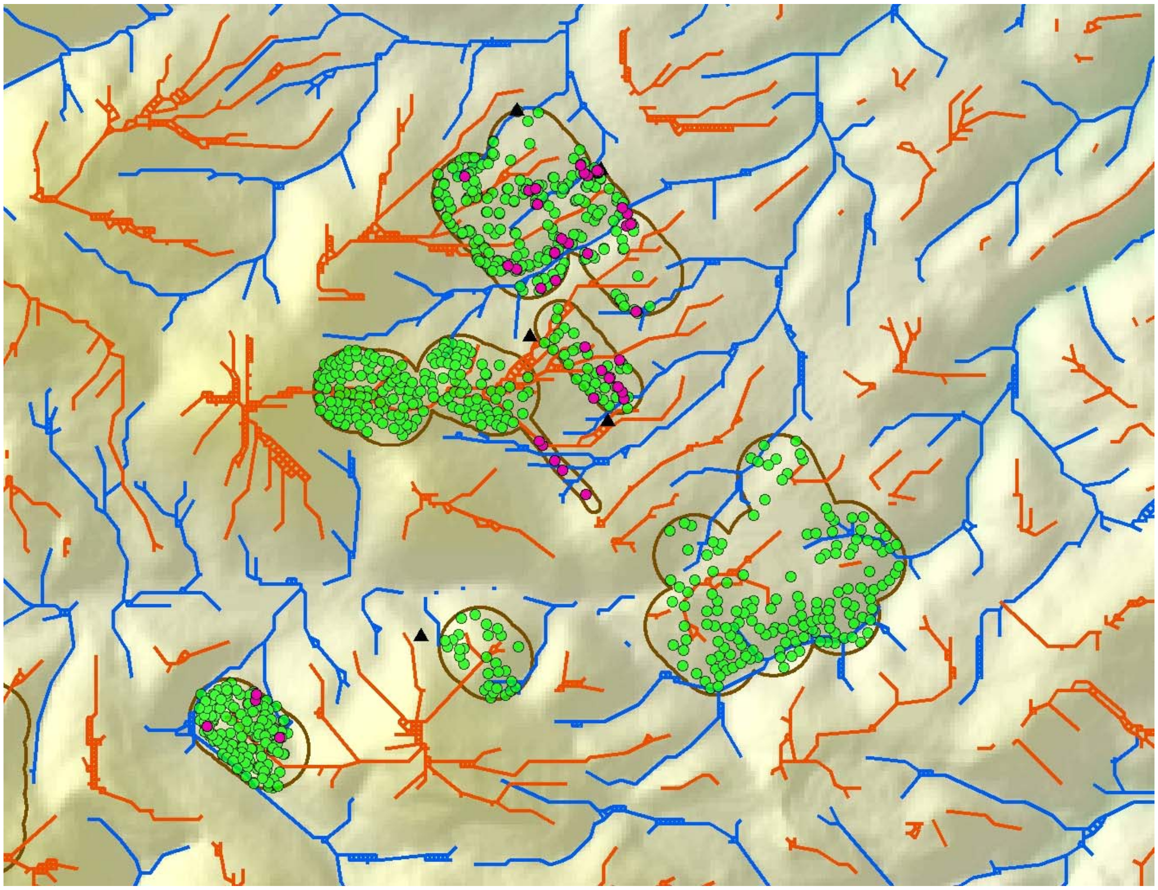


Figure 6. Line coverages of ridges (red) and valley bottoms (blue) following multiple geoprocessing steps assessing trends in neighboring DEM grid cells. Ground squirrel burrow systems are shown as green circles, burrowing owl burrows as magenta circles, and black-edged polygons are the burrow mapping study areas masked from the larger landscape coverage.
Source: Lee Neher

The horizontal distance (m) of each DEM grid cell was then measured from the nearest valley bottom and the nearest ridgeline, referred to as *distance to valley* and *distance to ridge*, respectively (Figure 7). These distances were measured from the DEM grid cell to the closest grid cell of a valley bottom or ridgeline, respectively, not including vertical differences in position. The total distance across the underlying slope was the sum of the distance to the valley bottom and the distance to the ridgeline, and expressed the size of the slope (*total slope distance*). The DEM grid cell's position in the slope was also expressed as the ratio of the distance to the valley and the distance to the ridge, referred to as the *distance ratio*. This expression of the grid cell's position on the slope removed the size of the slope as a factor.

The vertical differences between each DEM grid cell and the nearest valley bottom and nearest ridgeline were measured as elevation differences (Figure 7), and the elevation difference between the nearest valley bottom and the nearest ridgeline also expressed the size of the slope, but this time referred to as *elevation difference*. In addition to the trend in slope grade at each

DEM grid cell, the *gross slope* was measured as the ratio of *elevation difference* and *total slope distance* (Figure 7). The DEM grid cell's position on the slope was also expressed as the ratio of the elevation differences between the grid cell and the nearest valley and the grid cell and the nearest ridge, referred to as the *elevation ratio*.

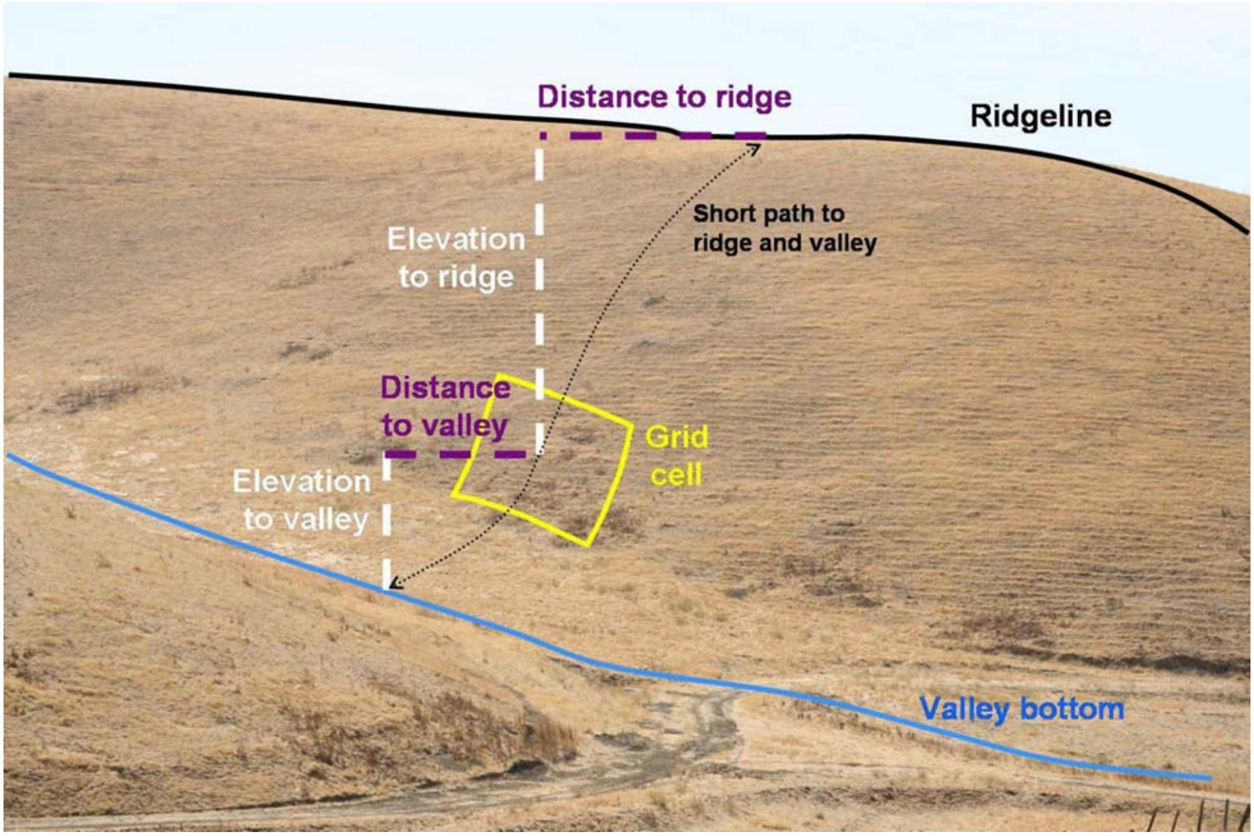


Figure 7. Example depiction of how slope attributes were measured from 10-m^2 DEM grid cells. The *elevation difference* was the Elevation to valley + Elevation to ridge, and *elevation ratio* was Elevation to valley ÷ Elevation to ridge. *Total slope distance* was Distance to valley + Distance to ridge, and *distance ratio* was Distance to valley ÷ Distance to ridge. *Gross slope* was *elevation difference* ÷ *total slope distance*. The hypothetical grid cell overlaps a burrowing owl burrow located on another project site in the APWRA.

Source: K Shawn Smallwood

Each DEM grid cell was classified by *slope aspect* according to whether it faced north, northeast, east, southeast, south, southwest, west, northwest, or it was on flat terrain. For analysis slope aspect was aggregated into five categories: northeast and east, southeast and south, southwest and west, northwest and north, and no aspect (flat terrain). Each grid cell was categorized as to whether its center on the landscape was windward, leeward or perpendicular to the prevailing southwest and northwest wind directions recorded during Smallwood and Thelander's (2004, 2005) behavior observation sessions.

Log_{10} and natural log transformations were used to better fit normal distributions, and then chi-square tests for association and principal components analysis (PCA) were used to further understand how the variables related to burrowing owl burrow locations and to each other. To minimize the effects of confounding, no more than one predictor variable was selected from each principle component for any model developed to classify grid cells according to whether they supported burrowing owl burrows. The first modeling approach used discriminant function analysis (DFA), and the second used fuzzy logic (Tanaka 1997, Kainz 2004). Both produced likelihood surface areas, one referred to as the DFA surface and the other as FL surface. The performance of each model was based on the lowest number of predictor variables, the smallest portion of the study area occurring within the likelihood surface area, and the most number of mapped burrows occurring within the likelihood surface.

Log_{10} *distance to valley* and *elevation difference* were the two variables used in fuzzy logic to predict the likelihood of each grid cell containing a burrowing owl burrow. These two variables were selected from a pool of candidates, based on relatively larger magnitudes of differences between mean values where burrowing owls were and were not found, and based on their relatively lower level of shared variation as judged from examination of a correlation matrix and the output from principal components analysis.

When the log_{10} distance to valley was < 0.81126 or > 1.73478, which was outside the mean ± 1 SD, or 1.27302 ± 0.46176, then the membership function of the grid cell belonging to the set with a burrowing owl burrow = 0 (Figure 8). If 0.81126 ≤ log_{10} distance to valley ≤ 1.158471, or between 1 SD and 1 SE less than the mean, then the membership function = 0.5×(1 - COS(3.14159 × (log_{10} distance to valley - 0.81126) ÷ (1.158471 - 0.81126))), and if 1.73478 ≥ log_{10} distance to valley ≥ 1.387569, or between 1 SD and 1 SE greater than the mean, then the membership function = 0.5×(1 + COS(3.14159 ×(log_{10} distance to valley - 1.387569) ÷ (1.73478 - 1.387569))). If 1.158471 < log_{10} distance to valley < 1.387569, which was within the mean 1.27302 ± SE of 0.114549, then the membership function = 1.

If the elevation difference was <3.68204 or >11.48716, which was outside the mean ± 4×SE, or 7.5846 ± 4 × 0.97564, then the membership function of the grid cell belonging to the set with a burrowing owl burrow = 0. If 3.68204 ≤ elevation difference ≤ 5.63332, or within 4× and 2×SE less than the mean, then the membership function = 0.5×(1 - COS(3.14159 × (elevation difference - 3.68204) ÷ (5.63332 - 3.68204))), and if 11.48716 ≥ elevation difference ≥ 9.53588, or within 4× and 2×SE greater than the mean, then the membership function = 0.5×(1 + COS(3.14159 × (elevation difference - 9.53588) ÷ (11.48716 - 9.53588))). If 5.63332 < elevation difference < 9.53588, which was within the mean 1.27302 ± SE of 0.114549, then the membership function = 1.

Based on log_{10} distance to valley, the grid cell's membership value in the burrowing owl burrow set was multiplied by 2.55×100, and based on elevation difference it was multiplied by 100 in order to obtain a value range that was easier to report and interpret. These two products were added and all sum values >70 used to obtain the fuzzy logic surface because 70 appeared to be a natural break in the frequency distribution. Finally, a *green zone*, representing what we hypothesized was a safer area for burrowing owls, was derived from grid cells both outside the fuzzy logic likelihood surface and on the leeward sides of hill structures relative to the two prevailing wind directions, which were southwest and northwest.

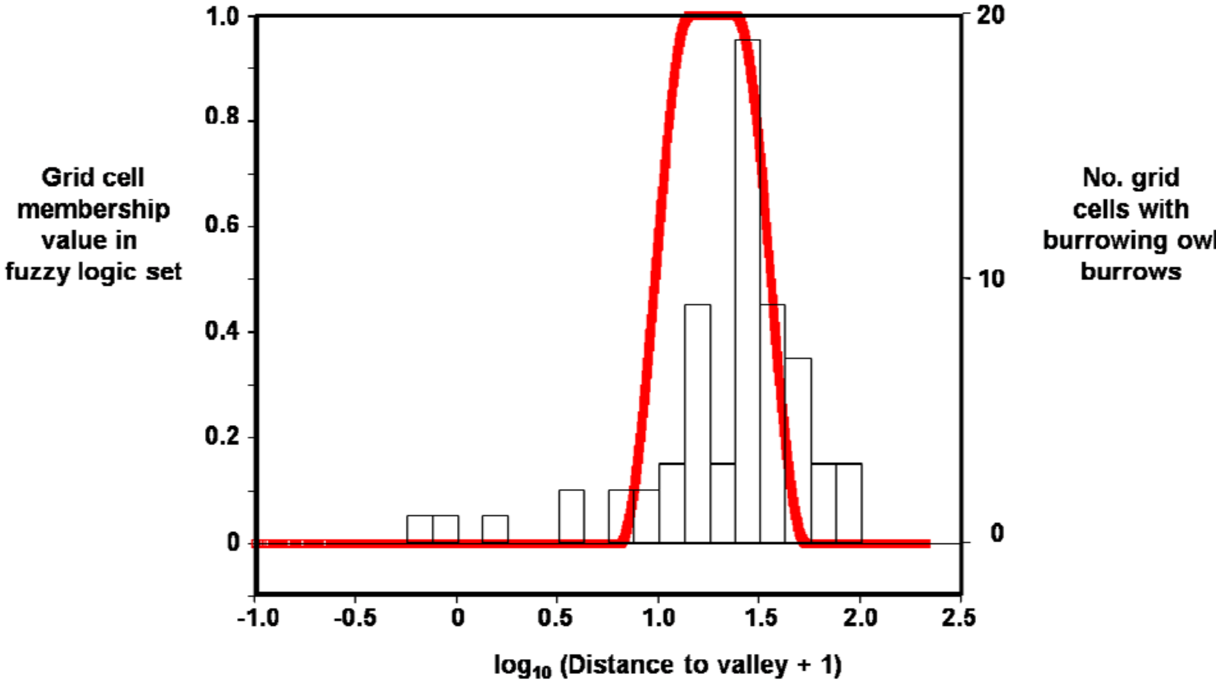


Figure 8. Example distribution of membership values in fuzzy logic set, in this case for grid cells containing burrowing owl burrows as a function of $\log_{10}$ distance to valley.

Source: K Shawn Smallwood

4.0 Results

4.1. Raptor Flight Observations

No additional analysis was performed on the 4,691 raptor flight and perching observations since Smallwood and Neher (2004). Instead, this study relied on Smallwood and Neher's (2004) rankings of grid cells by their exposure to the prevailing wind directions measured during the behavior observation sessions completed by Smallwood and Thelander (2004). The authors masked the landscape used for analysis of raptor flight observations similar to how they masked the burrowing owl data (Figure 9). This was used to relate owl flights to the landscape and prevailing wind directions (Figure 10).

Flights by red-tailed hawks, golden eagles, and American kestrels were significantly more common on the windward aspect of hills and ridges (Smallwood and Neher 2004). Locations of raptor flights shifted with wind direction to maintain flights where winds were strongest (i.e., declivity winds) (Figure 11). The authors related the locations of raptor flights to grid cells ranked by orientation to the two prevailing wind directions during the Smallwood and Thelander (2004) study and found that raptors flew disproportionately more often over slopes facing the prevailing wind directions (e.g., Figures 12 and 13). Based on this pattern, the authors used all grid cells on the leeward aspect to both northwest and southwest wind directions to create a zone that they considered to be safer for raptor flights (hereafter referred to as the *green zone*).

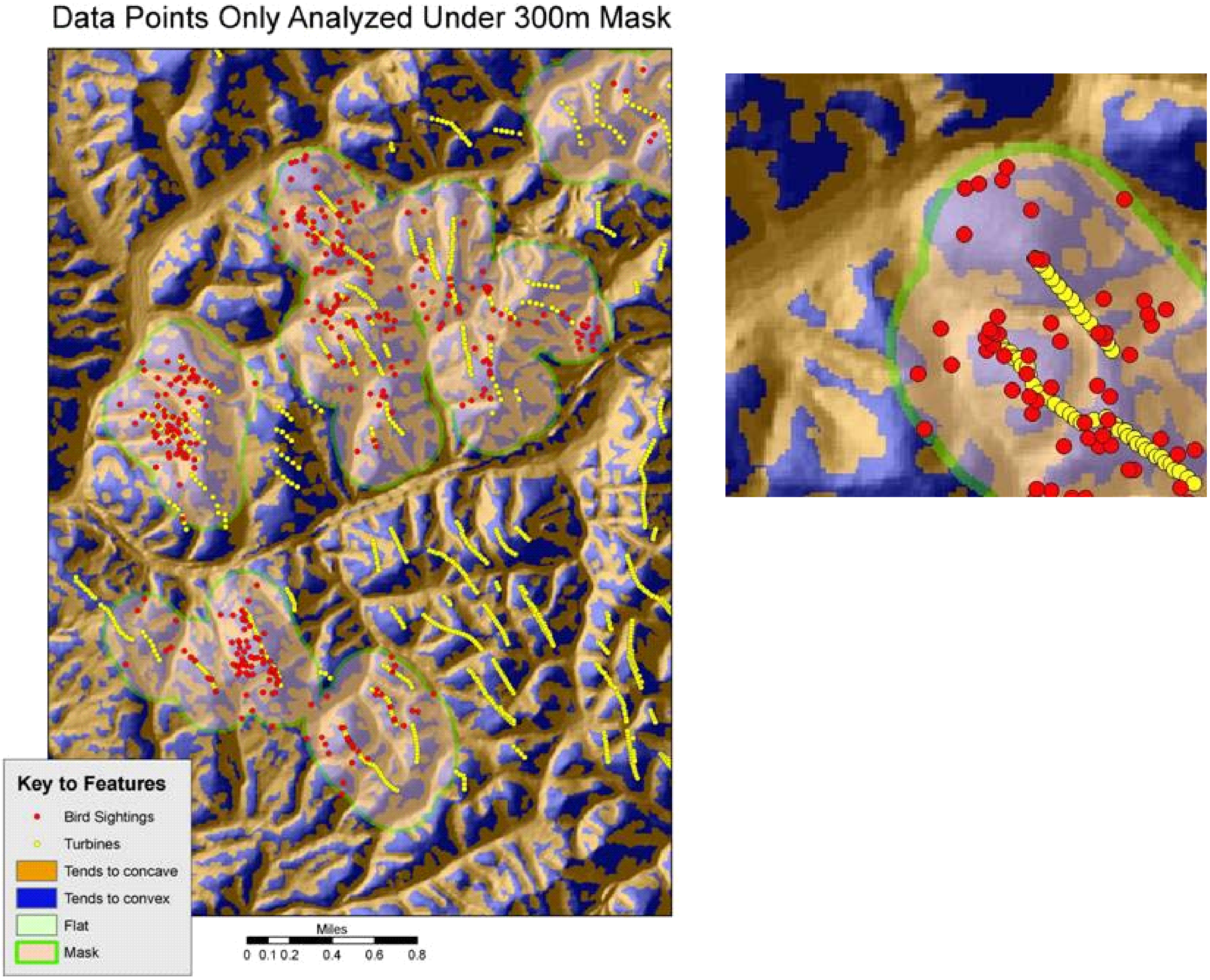


Figure 9. The study area used for analysis of raptor flight patterns was masked from the larger coverage of the landscape, where the mask was the 300-m distance from wind turbines included in each behavior observation plot. Red circles were raptor observations, and yellow circles were wind turbines. The derived coverage of the topography indicated 37.1% of the study area was composed of convex (ridge) features in blue, and the remaining 62.9% was composed of concave-trending features (valleys) in gold.

Source: Lee Neher

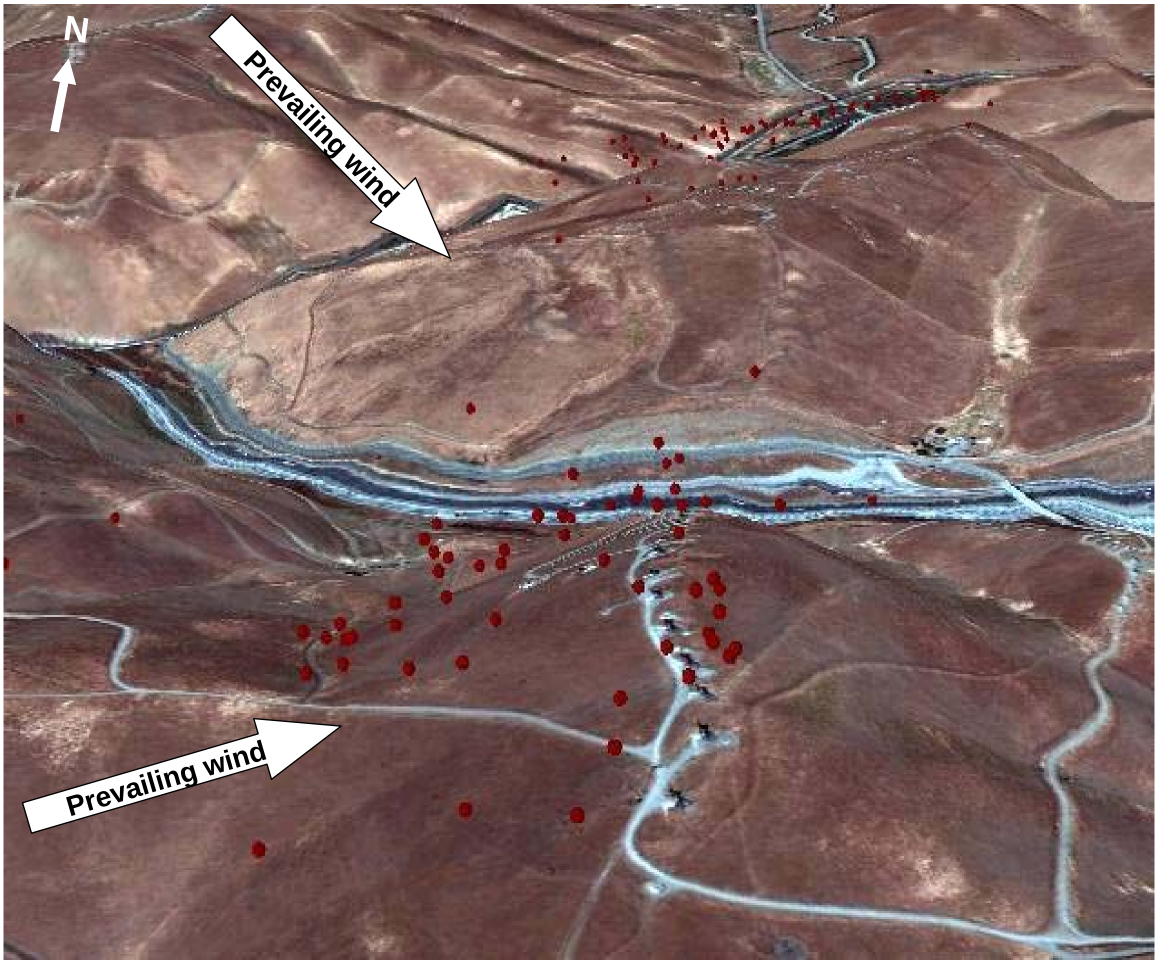
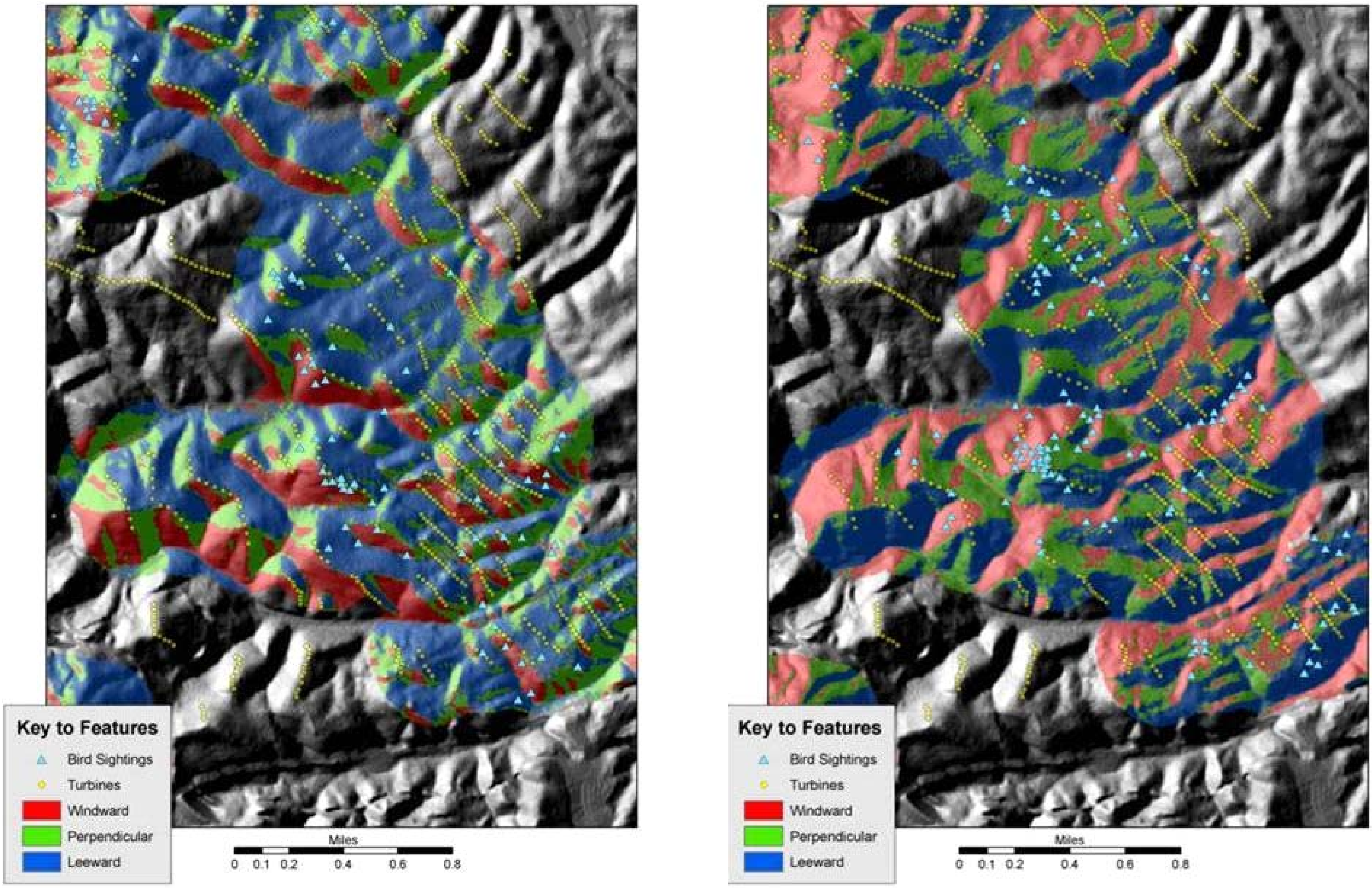


Figure 10. Sample of recorded raptor flight locations during the Smallwood and Thelander (2004) study, as well as the prevailing wind directions.

Source: Lee Neher

Southwest winds | **Northwest winds**



28% of wind observations | **31% of wind observations**

Figure 11. Samples of locations of observed raptor flights (blue triangles) shifted locations on the landscape according to wind direction during the observation sessions of Smallwood and Thelander (2004). Note that most of the raptor locations corresponded with the windward direction.

Source: Lee Neher

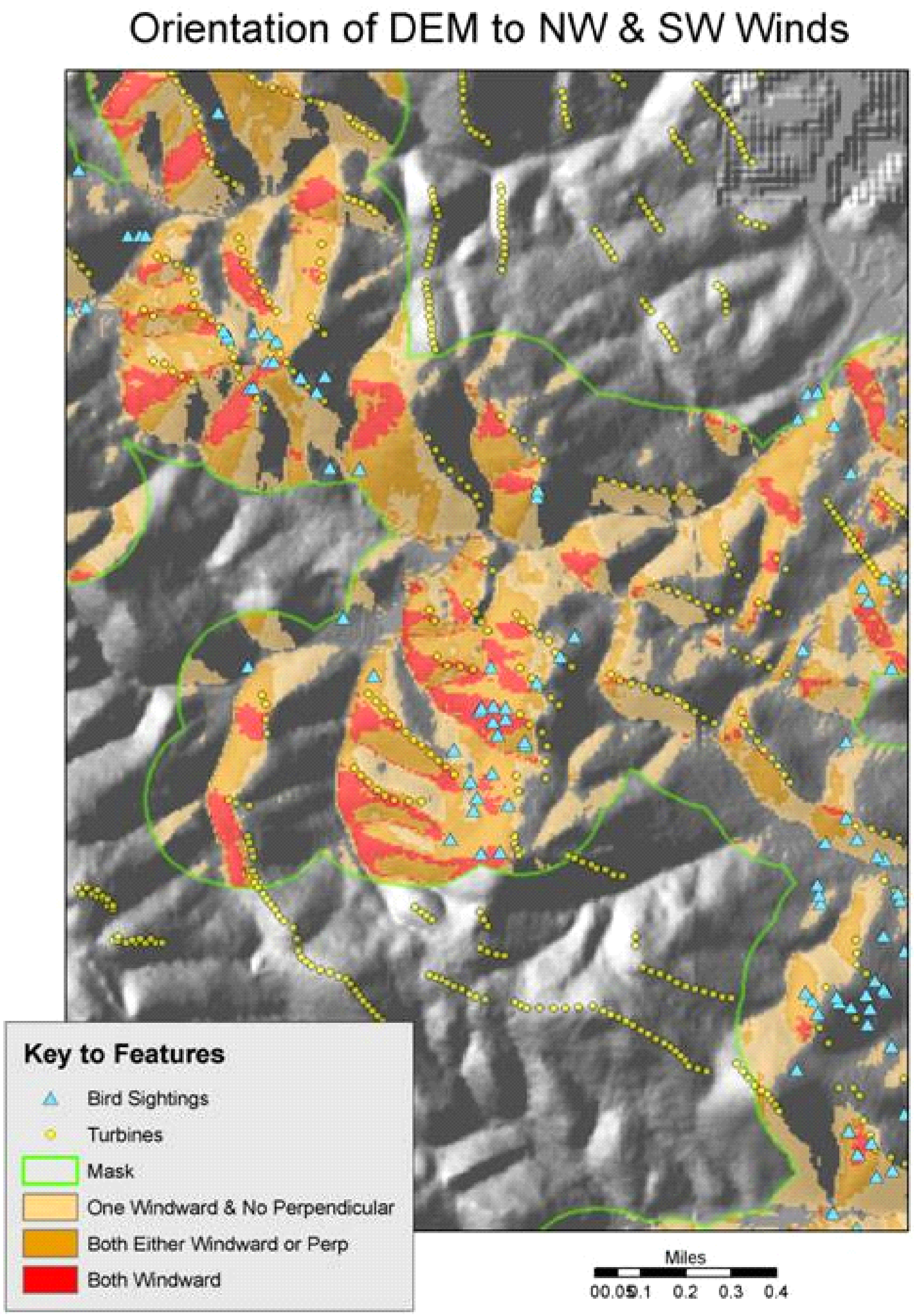


Figure 12. A sample of observed raptor flight locations relative to DEM grid cells ranked according to whether they are windward to both prevailing wind directions (red), windward to one direction and perpendicular to the other (orange), windward to one prevailing wind direction (light orange), and leeward to the prevailing wind directions (gray). Note most raptor flight locations were over grid cells windward to both directions or to at least one prevailing wind direction.

Source: Lee Neher

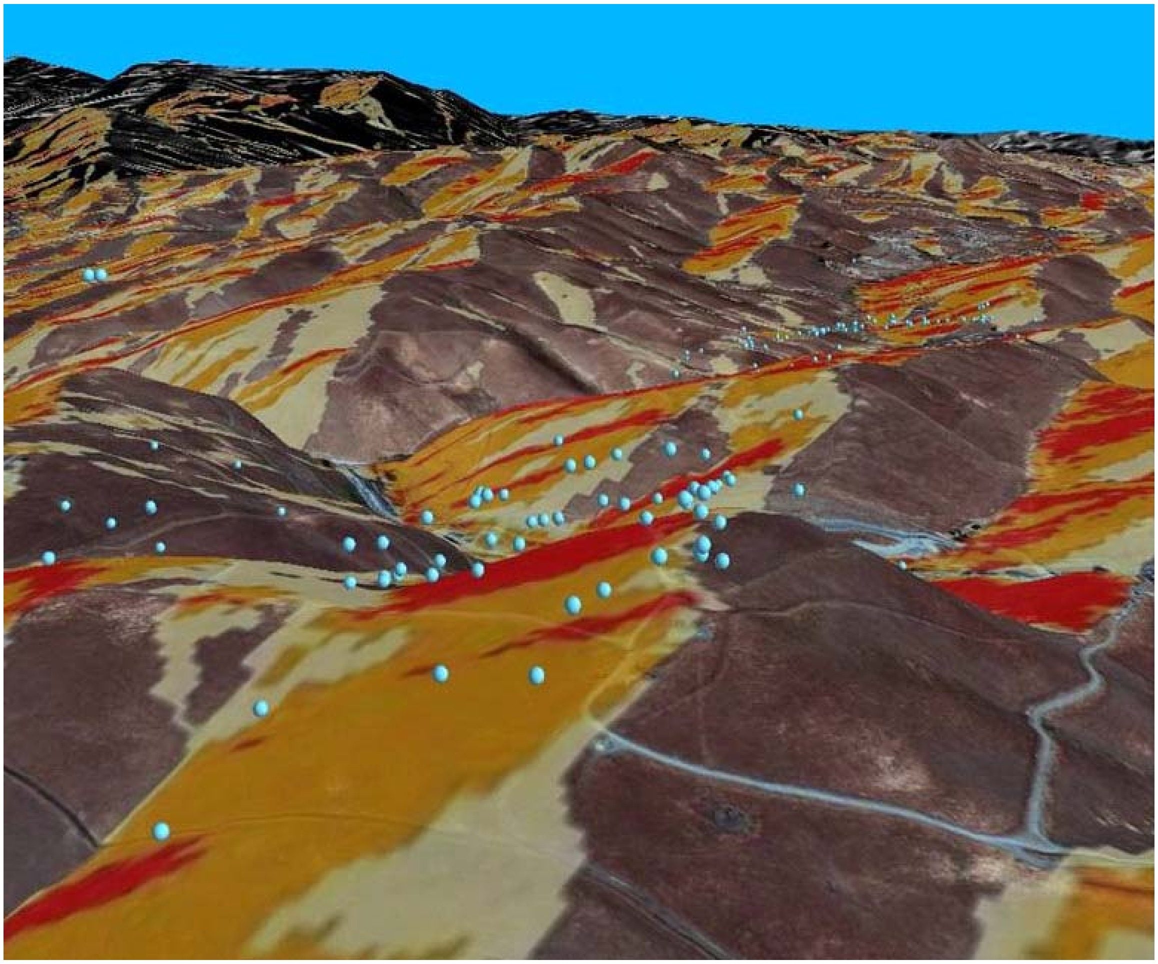


Figure 13. A sidelong view of a sample of observed raptor flight locations (bluer spheres) relative to DEM grid cells ranked according to whether they are windward to both prevailing wind directions (red), windward to one direction and perpendicular to the other (orange), windward to one prevailing wind direction (pale), and leeward to the prevailing wind directions (gray). Note most raptor flight locations were over grid cells windward to both directions or to at least one prevailing wind direction.

Source: Lee Neher

4.2. Burrowing Owl Burrow Locations

A principal components analysis, using a varimax rotation, explained 82% of the variation in the measured predictor variables among grid cells within the masked grid used for burrow analysis (Table 2). Component 1 can be interpreted as position on the slope. Component 2 can be interpreted as the slope's rate of change, i.e., steepness. Component 3 can be interpreted as the slope's size. Only one variable with a high loading was used from each component for subsequent predictive model development, though all variables and transformed variables were tested for a relationship with burrowing owl burrows.

Table 2. Principal Components following varimax rotation in PCA.

Variable	Component 1	Component 2	Component 3
ln Distance ratio	0.984		
ln Elevation ratio	0.907		0.133
$\log_{10}$ Distance to ridge	-0.872		0.312
$\log_{10}$ Distance to valley	0.800		0.480
Gross slope		0.908	0.175
Elevation difference		0.831	0.440
Slope (percentage)	-0.119	0.829	
Elevation	0.214	0.627	-0.191
$\log_{10}$ Total slope distance		0.159	0.927

Source: K. Shawn Smallwood and Lee K. Neher

Almost all measured slope attributes differed between sets of grid cells where burrowing owl burrows were found and where they were not found (Table 3). Grid cells with burrowing owl burrows averaged 47% of *distance to valley* compared to grid cells without burrowing owl burrows, and grid cells with owls averaged only 27% of the *distance ratio* compared to grid cells without owls (Table 3). Grid cells with burrowing owl burrows were located on slopes that averaged 72% of the *total slope distance* compared to grid cells without owl burrows, and these slopes averaged only 45% of the *elevation difference* between the nearest ridge and the nearest valley compared to cells without owl burrows. Grid cells with burrowing owl burrows were on slopes that averaged 56% of the *gross slope* compared to those without owl burrows, and they averaged 71% of the *percentage slope* specific to the grid cell. Grid cells with burrowing owl burrows averaged 22% of the *elevation ratio* compared to grid cells without owl burrows. Regardless of slope size, occupied grid cells were on average about a fifth of the *elevation difference* from valley bottoms compared to ridges.

Table 3. Mean comparisons between sets of grid cells where burrowing owl burrows were not found (n = 187,843) and where they were found (n = 65). To denote the significance of the ANOVA tests, * was P < 0.05, ** was P < 0.005, and no symbol indicated P > 0.05.

	Burrowing owl burrows				
	Not found		Found		ANOVA F-value
Variable	Mean	SD	Mean	SD	
Distance to valley (m)	61.58	37.29	29.25	19.12	48.84**
$\log_{10}$ Distance to valley	1.66	0.42	1.34	0.41	37.04**
Distance to ridge (m)	42.19	29.94	45.09	18.40	0.61
$\log_{10}$ Distance to ridge	1.45	0.50	1.59	0.31	5.26*
Total slope distance (m)	103.77	30.16	74.34	22.01	61.86**
$\log_{10}$ Total slope distance	2.00	0.14	1.85	0.13	67.54**
Distance ratio	5.37	11.26	1.44	3.33	7.90*
ln Distance ratio	0.46	1.63	-0.53	1.18	23.69**
Elevation (msl)	191.79	97.35	143.43	38.18	16.04**
Elevation difference; near ridge - near valley	17.06	12.18	7.71	8.02	38.30**
$\log_{10}$ Elevation difference	1.43	0.18	1.27	0.15	53.01**
Gross slope	0.16	0.10	0.09	0.07	30.85**
Slope (percentage)	18.86	12.19	13.38	8.17	13.12**
Elevation ratio	5.40	8.11	1.20	1.64	17.42**
ln Elevation ratio	0.60	1.67	-0.27	0.87	17.52**
$\log_{10}$ Elevation ratio	0.57	0.43	0.28	0.20	28.82**
Principal component 1, position on slope	0.0002	1.0000	-0.5301	0.6226	18.27**
Principal component 2, slope steepness	0.0002	1.0000	-0.6078	0.6265	24.02**
Principal component 3, slope size	0.0003	0.9999	-0.7678	0.9263	38.34**

Source: K. Shawn Smallwood and Lee K. Neher

The most efficient discriminant function analysis models were composed of fewer variables that correctly classified a higher percentage of grid cells where burrowing owl burrows were found (Table 4). *Elevation difference* helped produce the most efficient models (upper two rows of the table), and *total slope distance* and the natural log of the *elevation ratio* also contributed to these efficient models. Slope size contributed most to the DFA model developed from principal components estimated from the PCA, followed by slope steepness and position on the slope. According to this model, grid cells were more likely to be predicted to contain burrowing owl burrows closer to the valley bottom, and their corresponding slopes were smaller and shallower, as seen by the negative classification coefficients for burrow membership.

The most reliable assessment of each model in Table 4 was the percentage correct classification of grid cells where burrowing owls were found because grid cells, where burrowing owls were not found, could have contained burrowing owl burrows in the past and might support them in the future. Burrowing owls shift burrow locations occasionally, and population turnover will also result in a dynamic spatial distribution of burrows.

Table 4. The most efficient discriminant function models of grid cells predicted to have burrowing owl burrows or not, as well as a DFA model estimated from the PCA scores. All three models were significant (P < 0.0001).

Discriminant Functions (standardized canonical discriminant function coefficients)	Percent correct classification of grid cells	
	Where burrowing owl burrows were Found	Total
Total slope distance (0.77), Elevation difference (0.35)	84.6	67.4
Elevation difference (0.82), ln Elevation ratio (0.50)	87.7	62.3
Position on slope (0.48), Slope steepness (0.55), Slope size (0.69)	72.3	72.8

Source: K. Shawn Smallwood and Lee K. Neher

4.3. Spatial Model of Burrowing Owl Burrows

The DFAs performed reasonably well by correctly predicting 72% to 88% of the grid cells with burrowing owl burrows, but the spatial areas predicted to support burrowing owl burrows were relatively large. One DFA model correctly predicted 88% of known burrow sites, but also predicted that 38% of the study area would contain burrowing owl burrows (Figure 14).

Based on the authors' DFA model, the combinations of variables in Table 4 performed about as well as *elevation difference* and $\log_{10}$ *distance to valley* using fuzzy logic. These were selected from different PCs and shared a Pearson's correlation coefficient of only 0.27, so they were reasonably orthogonal. Of the 65 burrowing owl burrows in the study area, 57 (88%) were located on the FL surface based on FL values >10. This likelihood surface was 52% of the study area. Burrowing owl burrows associated with the fuzzy logic surface ($\chi^2 = 33.17$, df = 1, P < 0.001), and were mapped in it 1.69 times other than expected, i.e., 88% ÷ 52% = 1.69.

Of the 65 burrows of burrowing owls compared to GIS raster layers, 53 (81.5%) were located in the FL surface with values >70. This likelihood surface was 43.2% of the study area (Figure 15). Burrowing owl burrows associated with the fuzzy logic surface ($\chi^2 = 38.18$, df = 1, P < 0.001), and were mapped in the FL surface 1.89 times other than expected, i.e., 81.5% ÷ 43.2% = 1.89.

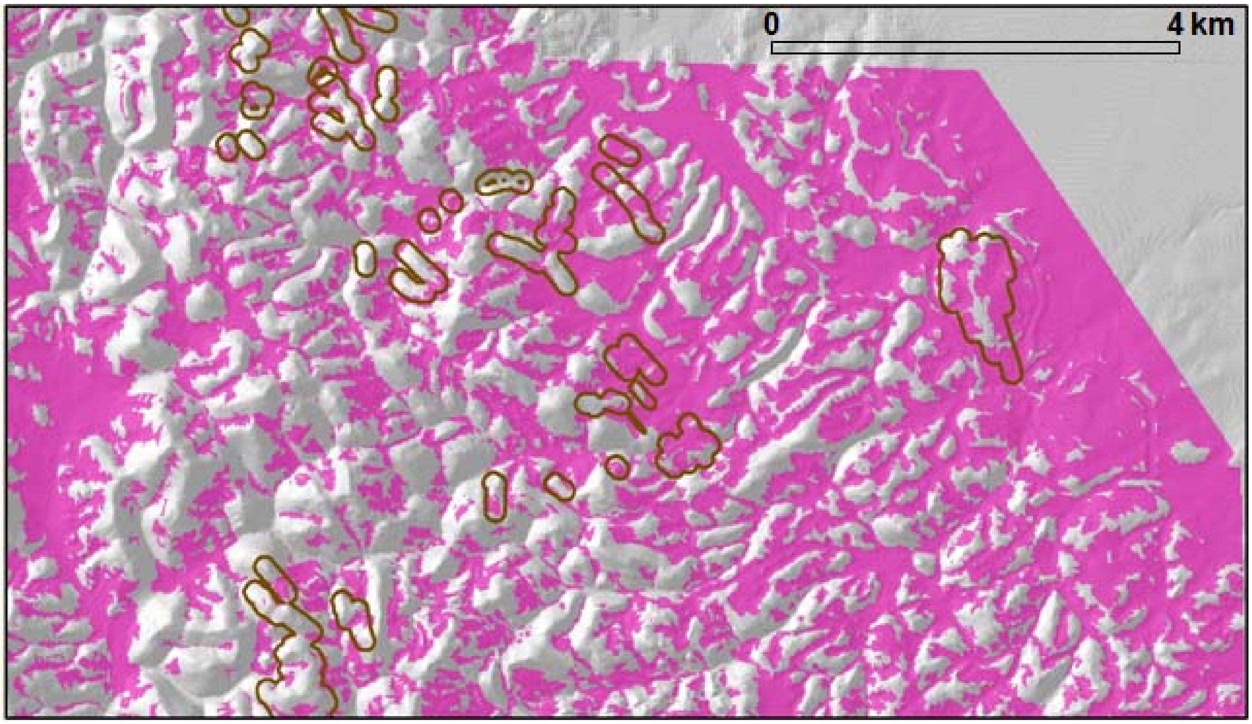


Figure 14. Areas (magenta) within the APWRA predicted to be selected by burrowing owls for burrow locations based on a Discriminant Function Model. Boundaries of some burrow mapping areas are shown in black.
Source: Lee Neher and K Shawn Smallwood

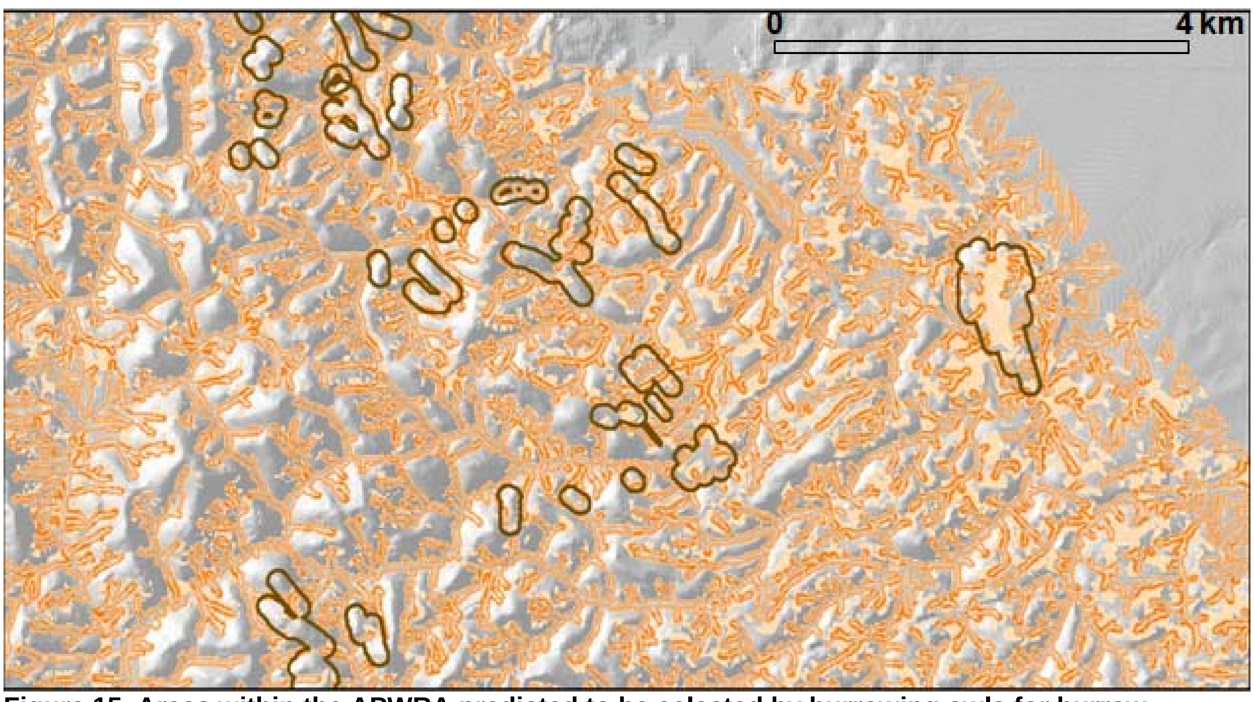


Figure 15. Areas within the APWRA predicted to be selected by burrowing owls for burrow locations based on a Fuzzy Logic Model and surface values >70, where the darker orange depict strongest prediction. Boundaries of some burrow mapping areas are shown in black.
Source: Lee Neher and K Shawn Smallwood

Relationships between spatial models and known fatality locations.—Fatalities of burrowing owls were 1.77 times more frequent other than expected on the DFA surface (Table 5). The DFA surface included 16.4% of the rated capacity in old-generation wind turbines that were searched for fatalities. Forty-nine of the recorded 69 burrowing owl fatalities occurred at wind turbines that were sampled outside the DFA surface, yet this area included 83.6% of the rated capacity for wind energy generation in the APWRA. Among all wind turbines in the APWRA (including those not sampled), 16.4% (89.55 MW) were in and 83.6% (456.23 MW) were out of the DFA surface area.

Fatalities of burrowing owls were 1.95 times more frequent than expected in the FL surface (values >70), where 22% of the rated capacity in sampled old-generation wind turbines was located (Table 6). Thirty-nine of the recorded 69 fatalities occurred at sampled wind turbines outside the FL surface, but this area included 77.7% of the rated capacity for wind energy generation in the APWRA. Among all wind turbines in the APWRA (including those not sampled), 27.3% (149.71 MW) were in and 72.7% (397.97 MW) were out of the DFA surface area.

The DFA surface also associated with disproportionately more wind turbine-caused fatalities of red-tailed hawk, mallard, western meadowlark, and mourning dove (Table 5). The FL surface also associated with disproportionately more wind turbine-caused fatalities of western meadowlark and mourning dove (Table 6).

Seventeen percent of the 69 burrowing owl fatalities were located at wind turbines in the green zone (Table 7), and there were disproportionately more burrowing owl fatalities outside the green zone ($\chi^2 = 4.95$, df = 1, $P > 0.05$). The areas outside the green zone were also associated with disproportionately more wind turbine-caused fatalities of golden eagle, barn owl, western meadowlark, and mourning dove (Table 7).

Unadjusted fatality rate estimates were consistently greater for bird species within the FL surface and usually greater outside the green zone (Table 8). The fatality rate of burrowing owl was nearly four times greater in the FL surface, and the overall bird fatality rate was nearly twice as great on this surface. The burrowing owl fatality rate was 1.64 times greater outside the green zone compared to inside the green zone, and the barn owl fatality rate was 8 times greater, and the mourning dove fatality rate was 4.4 times greater. However, the fatality rates of red-tailed hawk and American kestrel were greater in the green zone.

Based on the results and on the assumption that the avian fatality rate is related to the location of wind turbines, the authors predict that moving wind turbines off the FL surface might reduce the fatality rate of golden eagles by about 26%, American kestrels by about 49%, burrowing owls by about 74%, all raptors by about 33%, and all birds by about 46% (Table 9). However, the authors predict the fatality rate of red-tailed hawks and great horned owls might not change. Moving wind turbines into the green zone might reduce the fatality rate of golden eagles by roughly 20%, burrowing owls by about 39%, barn owls by roughly 88%, and all birds by about 23%. However, it might increase the fatality rate of red-tailed hawks by about 45%, American kestrels by 16%, and great horned owls nearly 300%. Thus, moving turbines to areas outside the

FL surface may likely lead to a marked reduction in bird fatalities compared to areas in the green zone.

Compared to the old-generation wind turbines existing during the Smallwood and Thelander (2004) study, a larger percentage of the planned and already-installed new wind turbines are located outside the FL surface and within the green zone (Table 10). Relatively minor adjustments to the planned locations of turbines during the repowering process could lead to substantial changes in these percentages in the FL surface and green zone because many of the planned new turbine locations within the FL surface and outside the green zone are within 10 to 20 m of the boundaries. Ten- to 20-m shifts of new turbine locations to the leeward aspects of hills relative to the prevailing winds would place most new turbines in the green zone.

Table 5. Fatalities off and on the sampled portion of the DFA surface in the APWRA, where the rated wind power capacity of turbines was 364.58 MW (84%) off the FL surface and 71.45 MW (16%) on the DFA surface. Significance of chi-square values were denoted by *t* for 0.10 > P > 0.05, * for P < 0.05, and ** for P < 0.005.

Test of Association	Observed fatalities		Expected fatalities	Observed ÷ expected fatalities	Chi-square
	Percent	Number			
Golden eagle					
Off DFA surface	86.8	46	44.32	1.04	
On DFA surface	13.2	7	8.68	0.81	0.390
Red-tailed hawk					
Off DFA surface	78.3	166	177.26	0.94	
On DFA surface	21.7	46	44.73	1.32	4.376*
American kestrel					
Off DFA surface	79.7	47	49.33	0.95	
On DFA surface	20.3	12	9.66	1.24	0.675
Burrowing owl					
Off DFA surface	71.0	49	57.69	0.85	
On DFA surface	29.0	20	11.30	1.77	8.003**
Barn owl					
Off DFA surface	79.6	39	40.97	0.95	
On DFA surface	20.4	10	8.03	1.25	0.580
Great horned owl					
Off DFA surface	70.6	12	14.21	0.84	
On DFA surface	29.4	5	2.78	1.80	2.107
Raptors					
Off DFA surface	78.4	403	429.77	0.94	
On DFA surface	21.6	111	84.19	1.32	10.203**
Mallard					
Off DFA surface	60.6	20	27.59	0.72	
On DFA surface	39.4	13	5.41	2.41	12.760**
Horned lark					
Off DFA surface	91.3	21	19.23	1.09	
On DFA surface	8.7	2	3.77	0.53	0.992
Western meadowlark					
Off DFA surface	73.7	70	79.43	0.88	
On DFA surface	26.3	25	15.56	1.61	6.846*
Mourning dove					
Off DFA surface	48.5	16	27.59	0.58	
On DFA surface	51.5	17	5.41	3.15	29.741**
Birds					
Off DFA surface	72.1	828	960.72	0.86	
On DFA surface	27.9	321	188.21	1.71	112.031**

Source: K. Shawn Smallwood and Lee K. Neher

Table 6. Fatalities off and on the sampled portion of the FL surface (values >70) in the APWRA, where the rated wind power capacity of turbines was 340.04 MW (78%) off the FL surface and 97.80 MW (22%) on the FL surface. Significance of chi-square values were denoted by *t* for 0.10 > P > 0.05, * for P < 0.05, and ** for P < 0.005.

Test of Association	Observed fatalities: Percent	Observed fatalities: Number	Expected fatalities	Observed ÷ expected fatalities	Chi-square
Golden eagle					
Off FL surface	66.7	36	41.16	0.92	
On FL surface	33.3	18	11.84	1.27	1.087
Red-tailed hawk					
Off FL surface	38.5	146	164.64	0.95	
On FL surface	31.5	67	47.35	1.18	2.032
American kestrel					
Off FL surface	62.7	37	45.82	0.87	
On FL surface	37.3	22	13.18	1.44	3.311 ^{t}
Burrowing owl					
Off FL surface	49.3	34	53.59	0.73	
On FL surface	50.7	35	15.41	1.95	17.777**
Barn owl					
Off FL surface	67.3	33	38.05	0.92	
On FL surface	33.7	16	10.95	1.28	1.098
Great horned owl					
Off FL surface	61.1	11	13.20	0.83	
On FL surface	38.9	7	3.80	1.58	1.645
Raptors					
Off FL surface	64.0	331	399.19	0.89	
On FL surface	36.0	186	114.81	1.38	20.917**
Mallard					
Off FL surface	63.6	21	25.63	0.86	
On FL surface	36.4	12	7.37	1.49	2.300
Horned lark					
Off FL surface	65.2	15	17.86	0.90	
On FL surface	34.8	8	5.14	1.36	0.869
Western meadowlark					
Off FL surface	59.4	57	63.78	0.84	
On FL surface	40.6	39	21.22	1.56	8.420**
Mourning dove					
Off FL surface	47.1	16	25.63	0.66	
On FL surface	52.9	18	7.37	2.17	13.006**
Birds					
Off FL surface	60.1	695	892.34	0.84	
On FL surface	39.9	461	256.65	1.55	101.657**

Source: K. Shawn Smallwood and Lee K. Neher

Table 7. Fatalities outside and within the sampled portion of the green energy zone in the APWRA, where the rated wind power capacity of turbines was 385.35 MW (70%) outside the green zone and 162.23 MW (30%) inside the green zone. Significance of chi-square values were denoted by *t* for 0.10 > P > 0.05, * for P < 0.05, and ** for P < 0.005.

Test of Association	Observed fatalities: Percent	Observed fatalities: Number	Expected fatalities	Observed ÷ expected fatalities	Chi-square
Golden eagle					
Outside green zone	85.2	46	38.00	1.21	
In green zone	14.8	8	16.00	0.50	5.682*
Red-tailed hawk					
Outside green zone	73.2	156	149.89	1.04	
In green zone	26.8	57	63.11	0.90	0.839
American kestrel					
Outside green zone	71.2	42	41.52	1.01	
In green zone	28.8	17	17.48	0.97	0.019
Burrowing owl					
Outside green zone	82.6	57	48.56	1.17	
In green zone	17.4	12	20.44	0.59	4.955*
Barn owl					
Outside green zone	89.8	44	34.48	1.28	
In green zone	10.2	5	14.52	0.34	8.866**
Great horned owl					
Outside green zone	66.7	12	12.67	0.95	
In green zone	33.3	6	5.33	1.13	0.119
Raptors					
Outside green zone	77.9	403	363.83	1.11	
In green zone	22.1	114	153.17	0.74	14.235**
Mallard					
Outside green zone	66.7	22	23.22	0.95	
In green zone	33.3	11	9.78	1.13	0.217
Horned lark					
Outside green zone	65.2	15	16.19	0.93	
In green zone	34.8	8	6.81	1.17	0.293
Western meadowlark					
Outside green zone	83.3	80	67.56	1.18	
In green zone	16.7	16	28.44	0.56	7.734*
Mourning dove					
Outside green zone	91.2	31	23.93	1.30	
In green zone	8.8	3	10.07	0.30	7.058*
Birds					
Outside green zone	77.6	897	813.51	1.10	
In green zone	22.4	259	342.49	0.76	28.920**

Source: K. Shawn Smallwood and Lee K. Neher

Table 8. Comparisons of unadjusted mortality estimates within and outside likelihood surfaces and green zone.

Species	Fatality rates (Fatalities/MW/yr)								
	On DFA surface	Off DFA surface	On ÷ off DFA surface	On FL surface	Off FL surface	On ÷ off FL surface	Outside green zone	Green zone	Outside ÷ inside green zone
Golden eagle	0.0700	0.0521	1.34	0.0784	0.0476	1.65	0.0587	0.0467	1.26
Red-tailed hawk	0.2238	0.1926	1.16	0.2101	0.1936	1.09	0.1751	0.2541	0.69
American kestrel	0.0676	0.1120	0.60	0.1495	0.0876	1.71	0.0986	0.1142	0.86
Burrowing owl	0.2038	0.0535	3.81	0.1710	0.0523	3.27	0.0920	0.0562	1.64
Barn owl	0.0585	0.0500	1.17	0.0702	0.0452	1.55	0.0686	0.0085	8.06
Great horned owl	0.0162	0.0068	2.36	0.0076	0.0089	0.85	0.0046	0.0184	0.25
Mallard	0.0547	0.0197	2.77	0.0605	0.0149	4.06	0.0277	0.0226	1.23
Mourning dove	0.1707	0.0298	5.72	0.1300	0.0381	3.42	0.0782	0.0178	4.39
Western meadowlark	0.2108	0.1352	1.56	0.1845	0.1432	1.29	0.1725	0.1059	1.63
Raptors	0.6443	0.4910	1.31	0.6987	0.4580	1.53	0.5240	0.5028	1.04
Birds	2.3201	1.1664	1.99	2.1638	1.1446	1.89	1.4956	1.1552	1.29

Source: K. Shawn Smallwood and Lee K. Neher

Table 9. Calculated changes in estimated fatality rates if all wind turbines on the FL surface were moved off the surface, and if all wind turbines outside the green zone were moved inside the green zone.

Species	Percent change in annual APWRA fatalities if all existing turbines were located:		
	Off DFA surface	Off FL surface	In green zone
Golden eagle	-5	-13	-15
Red-tailed hawk	-2	-2	+28
American kestrel	+7	-14	+11
Burrowing owl	-31	-34	-31
Barn owl	-2	-11	-83
Great horned owl	-18	+3	+112
Mallard	-22	-41	-14
Mourning dove	-43	-35	-70
Western meadowlark	-8	-6	-31
Raptors	-5	-11	-3
Birds	-14	-17	-17

Source: K. Shawn Smallwood and Lee K. Neher

Table 10. Distributions of old- and planned new-generation wind turbines outside of modeled likelihood surfaces and within the green zone.

Wind turbines	Total no. of wind turbines	Turbines off DFA surface		Turbines off FL surface		Turbines in green surface	
		Number	Percent	Number	Percent	Number	Percent
Existing old-generation turbines	5301	4310	81.3	3724	70	1503	28
Proposed new turbines	203	178	87.7	165	81	68	33

Source: K. Shawn Smallwood and Lee K. Neher

4.4. Relationships of Burrowing Owl Burrows With Ground Squirrel Burrow Systems

The authors compared slope attributes of grid cells without ground squirrel or burrowing owl burrows (empty cells) to cells with ground squirrels and to cells with burrowing owls (Table 11). Grid cells with ground squirrel burrows were significantly closer to the valley bottom than were empty cells, and those with burrowing owl burrows were significantly closer than both empty cells and cells with ground squirrel burrows (Table 11, Figure 16). Grid cells with ground squirrel and burrowing owl burrows were at significantly lower elevations than the average empty cell.

Table 11. Mean comparisons among sets of grid cells containing ground squirrel burrow systems, burrowing owl burrows, and no ground squirrel or burrowing owl burrows (empty cells), where post-hoc least significant difference tests were denoted by *a* for tests between empty cell and ground squirrel, *b* for empty cell and burrowing owl, and *c* for ground squirrel and burrowing owl, and the overall ANOVA df = 1, 187,907. Sample sizes were n = 185,077 for empty cells, n = 2,766 for cells with ground squirrels, and n = 65 for cells with burrowing owls.

Predictor variable	Empty cell	Mean Ground squirrel	Burrowing owl	ANOVA F-value	Least-significant differences
Distance to valley	61.80	46.38	29.25	466.80**	abc
Distance to ridge	42.12	46.69	45.09	63.31**	a
Total slope distance	103.93	93.06	74.34	353.47**	abc
Distance ratio	5.40	3.33	1.45	92.27**	ab
Elevation	192.55	140.75	143.43	774.58**	ab
Elevation difference	17.12	12.98	7.71	176.64**	abc
Elevation ratio	5.43	2.86	1.20	274.78**	ab
Gross slope (×100)	15.87	13.28	9.14	112.26**	abc
Slope (percent)	18.89	17.12	13.38	57.23**	abc
Principal component 1	0.0049	-0.3128	-0.5301	146.83**	ab
Principal component 2	0.0053	-0.3433	-0.6078	178.02**	abc
Principal component 3	0.0027	-0.1650	-0.7678	57.53**	abc

Source: K. Shawn Smallwood and Lee K. Neher

According to the factor scores from the PCA, burrows of ground squirrel and burrowing owl were significantly closer to the valley bottom than the average empty grid cell, and they were on significantly shallower and smaller slopes. Relative to the average grid cell with ground squirrel burrows, grid cells with burrowing owl burrows were on significantly shallower and smaller slopes (Figure 17).

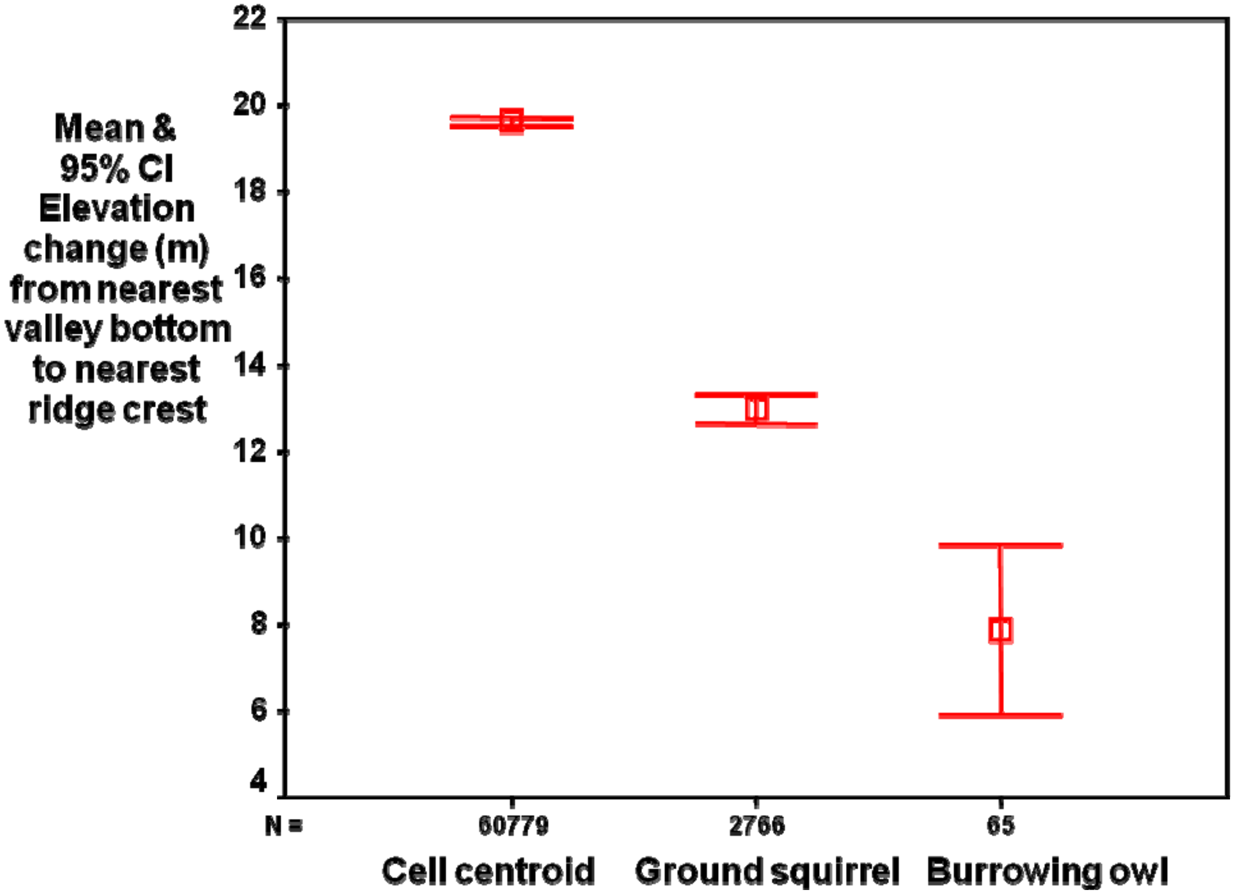


Figure 16. The mean and 95% confidence interval of the elevation difference between grid cells at the nearest valley bottom and those containing burrowing owl burrows was smaller than for cells with ground squirrel burrows, and was smaller for cells with burrowing owl or ground squirrel burrows than for grid cells without burrows. In other words, ground squirrel burrows on average were located relatively low on the slope, and burrowing owls were lower still.

Source: K Shawn Smallwood

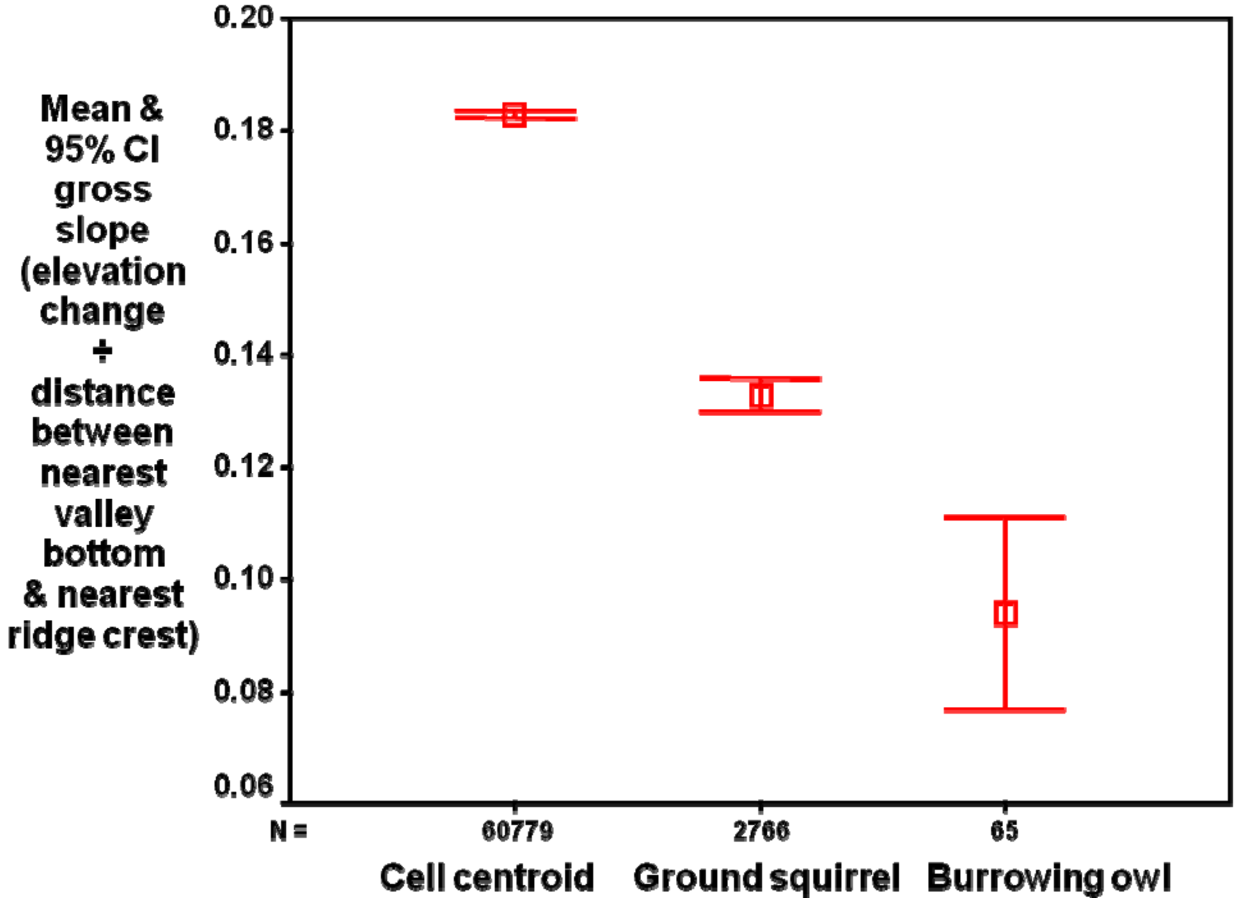


Figure 17: The mean and 95% confidence interval of the gross slope was smaller for grid cells with burrows of burrowing owls than for those with burrows of ground squirrels, and it was smaller for grid cells with burrows of either burrowing owls or ground squirrels compared to cells without burrows. In other words, ground squirrel burrows on average were located on shallower slopes than the average grid cell in the APWRA, and burrowing owl burrows were on even shallower slopes.

Source: K Shawn Smallwood

5.0 Discussion

Burrowing owls used burrows low on the slope, and on shallower, smaller slopes than where the average grid cell was located without burrowing owl burrows. Ground squirrel burrows also occurred lower on slopes and disproportionately more often on shallower, smaller slopes. However, the authors did not find that burrowing owls used ground squirrel burrows at random, but rather they used shallower, smaller slopes. *Slope aspect* appeared important for the location of burrowing owl burrows at the start of the study, but no association remained with their locations after accounting for other slope characteristics because some of the measured slope attributes correlated with *slope aspect*.

Models derived from discriminant function analysis supported the mean comparisons, suggesting slope size and relatively lower positions on the slope were important predictors of burrowing owl burrow locations. These patterns were further supported by the various combinations of variables tried in developing fuzzy logic models.

The fuzzy logic approach resulted in the most efficient model of burrowing owl burrow site selection. This model produced a likelihood surface in which the burrows of burrowing owls occurred almost twice as often other than expected. The distance to the nearest valley bottom contributed strongest to the model. Burrowing owls appear to select ground squirrel burrows toward the bottoms of the slopes, but usually just outside the flatter portions of the terrain normally regarded as valley bottoms. Burrowing owl burrows usually occur on portions of slopes where it is difficult to define where the boundary exists between the valley and the slope of the hill. The hypothetical grid cell in Figure 4 exemplifies the areas selected by burrowing owls, since a burrow was mapped there.

Possible reasons for selecting this aspect of the terrain include improved visibility for predator detection, improved auditory detection of approaching predators, improved predator escape opportunities, and improved foraging opportunities. The locations selected by burrowing owls appeared to offer superior views of the valley bottom, which are often patrolled by mammalian carnivores. These sites are also outside the windiest portions of the APWRA, which are near ridge crests where declivity winds are considerably stronger and noisier. Declivity winds are those pushed up the slope, hence passing over the higher terrain under greater pressure. Burrowing owls located low on the slope might hear approaching raptors more often without the distracting, camouflaging noise of the declivity winds. Locations low on the slope also provide burrowing owls opportunities to find refuge in many neighboring ground squirrel burrows, but because they are not on the valley bottom and likely receiving more winds than at the valley bottom, they are likely more capable of getting lift upon takeoff. Finally, prey items might be more abundant lower on the slope, and this zone might form somewhat of a catch for large flying insects. Further, focused research of burrowing owls in the APWRA might reveal why burrowing owls select the lower aspects of shallower, smaller slopes.

Another possible reason for burrowing owls residing in burrows low on the slope is to avoid wind turbines. Leddy et al. (1999) found that grassland songbirds tended to nest farther from wind turbines, demonstrating an avoidance behavior. Burrowing owls might also avoid wind turbines by nesting toward the bottoms of slopes, where wind turbines were installed more rarely. Whether burrowing owls select burrows to avoid wind turbines can be partially tested on a study area in the APWRA without wind turbines, such as Vasco Caves Regional Preserve.

5.1. How the Spatial Model of Burrowing Owl Burrows Related to Fatalities

Nearly twice the number of burrowing owl fatalities were found at wind turbines in the valley transition zone other than expected of a uniform distribution of fatalities, generally confirming the results of Smallwood et al. (2001). Burrowing owl fatality rate at wind turbines in this zone was nearly four times the fatality rate outside it. Fatalities of other bird species caused by wind turbines were also associated with the valley transition zone, including for all raptors as a group and all birds as a group. Reasons for why this zone killed more raptors and birds include the disproportionate number of end-of-row turbines in this zone, which have repeatedly been associated with more fatalities (Orloff and Flannery 1992, Smallwood and Thelander 2004, Smallwood et al. 2007), and the presence of high densities of ground squirrel burrow systems. Birds might often fly into the valley transition zone while attempting to fly around the rows of wind turbines, which often descend slopes and end in this zone. Birds likely also fly through the APWRA more often by using the lowest portions of the landscape, which happens to coincide with the valley transition zone as well as the valley bottoms. Raptors might often perform predatory attacks in the valley transition zone because this is where most of the ground squirrel burrows occur, along with many of their prey items. The authors speculate that while foraging, raptors may be more susceptible to colliding with wind turbines because foraging raptors are momentarily fixated on prey items, which may reduce their focus on the wind turbines (Smallwood and Thelander 2004).

A possible third reason for the valley transition zone being more lethal to birds after wind turbines are installed there relates to wind turbine density. The APWRA-wide DEM averaged 430.33 grid cells per old-generation wind turbine, including 843.51 within the valley transition zone, and 255.36 outside the valley transition zone. The density of wind turbines in the valley transition zone has been 3.3 times lower than outside the valley transition zone. Smallwood and Thelander (2004, 2005) found lower density turbine fields associated with disproportionately more raptor fatalities, which was consistent with the authors’ finding here.

The green zone related to fatality rates more weakly than the valley transition zone, but overall still associated with reduced fatality rates. For some species, however, the green zone appeared more dangerous. Whereas the barn owl fatality rate was four times greater outside the green zone, great horned owl fatality rate was eight times greater in the green zone. Therefore, moving wind turbines in the green zone would benefit barn owls at great cost to great horned owls. Also, red-tailed hawk and American kestrel fatality rates were higher in the green zone. Focused research on species-specific behaviors and flight locations might lead to a superior green zone.

The green zone developed in this study leaves considerable space for the installation of new wind turbines as the APWRA is repowered. It leaves additional space if wind turbines are restricted to only areas outside the valley transition zone, which the authors recommend. Overall, it would appear new-generation wind turbines will likely kill fewer birds if they are installed on larger slopes outside the valley transition zone. New-generation wind turbines could further reduce fatalities of some or most of the species using the APWRA due to their increased tower heights, so long as the lowest reaches of their blades are significantly higher above the ground compared to the existing, old-generation turbines. Factoring in taller towers might also qualify smaller hills as nearly equally suitable to the installation of new wind turbines on large hills, from the point of view of burrowing owl fatalities. Burrowing owls and American kestrels generally do not fly as high as the turbine blades are located in the Diablo Winds and Buena Vista Wind Energy projects, so they might collide with these turbines rarely, regardless of hill size. Nevertheless, it would be prudent to avoid siting new turbines in the valley transition zone.

5.2. Future Research Needs

These analyses provided a map-based predictive model of where burrowing owls reside in the APWRA. The model could be improved by extending the effort to map burrows across larger areas in the APWRA, including more of the terrain not typically used to install wind turbines. Flight behaviors of burrowing owls could also be related to the terrain represented on the DEM and extended across the APWRA to predict dangerous versus safe zones. Similarly, intensive study of burrowing owl burrow sites and flight patterns could be studied at a reference site (i.e., Vasco Caves Regional Preserve in Contra Costa County, California) for comparison to sites with wind turbines. Study in a reference site would be particularly important because Smallwood and Thelander (2004) relied on multiple lines of evidence to suggest the existing wind turbines in the APWRA have affected flight patterns of some species, including burrowing owls. Study at Vasco Caves or a similar area might yield flight patterns in the Altamont Hills where no wind turbines are present to affect the flight patterns.

The predictive models of this study relied largely on burrowing owl burrow locations and only grossly considered observed flights of other raptor species. The green zone consisted simply of the areas outside the valley transition zone, which was based on burrowing owl burrow locations, and on the leeward sides of hills and ridges, which was the aspect of the terrain largely unvisited by flying raptors while winds blew from the northwest, west, and southwest. However, red-tailed hawk and American kestrel fatalities were disproportionately more numerous in the green zone, so the green zone did not perform well for all species. A new, more effective green zone might be developed by applying the fuzzy logic approach to GIS coverages of flight locations of each species separately.

The predictive models of this study also relied on the burrows that were mapped by Smallwood during his studies between 1999 and 2003, but his mapping efforts were focused largely on the terrain immediately surrounding the wind turbines. In some cases, he mapped burrows at valley bottoms and other terrain farther from wind turbines, but only where he mapped entire turbine fields including multiple wind turbine rows. Most of the mapping effort was made within 90 m of wind turbines, meaning the ridge crest and hill slopes to either side of the ridge crest. As a result, ridge crests were likely over-represented in the mapped area used for the models, and the APWRA likely includes more valley bottom and lower-slope terrain than the authors used for model development. A recently completed study in the Vasco Caves Regional Preserve, which is within the APWRA boundary, overcomes this shortfall by mapping burrows over the entire study area there, which is hundreds of hectares. This study will be useful for validating the models developed herein and for improving on them.

This study did not distinguish between nesting and non-nesting burrowing owl burrows, and it remains unknown whether the distinction would matter. However, the ongoing study at Vasco Caves is distinguishing between nesting and non-nesting burrows, though the number of wind turbines included in the study may be insufficient to yield strong patterns. It remains to be established whether burrowing owls are more susceptible to wind turbine collision whether they originate from nesting or non-nesting burrows. It also remains a possibility that some burrowing owls killed by wind turbines are not residents.

If there is significant spatial variation in scavenger removal of wind-turbine-killed birds, then our results could be biased. Scavenger removal rates could vary more than expected among bird species. For example, if corvids routinely patrol wind turbines for dead songbirds, then the recorded fatalities could compose only a small, unreliable subset of the number of songbirds actually killed. Small raptors, such as burrowing owl and American kestrel, might also be removed at higher rates than anticipated. Locations where corvids are more likely to patrol turbines might present fatality searchers with carcasses that are smaller proportions of killed birds, and turbines near wooded areas or many rock outcrops might be visited more frequently by foxes and coyotes. Turbines in low-lying areas, which is where this study found more ground squirrels reside, also could present fatality searchers with fewer of the actually killed birds because ground squirrels pull carcasses into their burrows. And if this was the case, then this study might have underestimated fatality rates of multiple bird species in the valley transition zone. Focused research on scavenger removal rates throughout the APWRA would reduce the uncertainty introduced by scavenger removal.

Another potential source of bias in our study was misattribution of burrowing owl fatalities to wind turbines. At least some of the burrowing owl fatalities found by fatality searchers in the APRWA may have resulted from predation. Predation rates might be higher at certain locations or slope conditions, thus causing a spurious relationship of fatalities attributed to wind turbines. A more focused study of burrowing owl behavior and predation in the APWRA would remove the uncertainty over cause of death.

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7.0 Glossary

APWRA	Altamont Pass Wind Resource Area
DFA	Discriminant function analysis
DRG	Digital rastor graphics
FL	Fuzzy Logic
F-MIN	Bird Fatality Minimizing Scenario
GIS	Geographic Information System
GPS	Global Positioning System
kW	Kilowatts of power generation (used as rating of wind turbine capacity)
LLNL	Lawrence-Livermore National Laboratory
m	Meters (international unit of distance measurement)
m/s	Meters per second
MSL	Mean sea level, used as a reference elevation
MW	Megawatts of rated power generating capacity of a wind turbine
P-MAX	Power maximizing scenario
USGS	United States Geological Survey